Report from the Expert Panel (EP) on the evaluation of the ARK VRZ commitment during the 2021/22 fishing season

<u>Members of the ARK Commitment Expert Panel 2022</u>:

Simeon Hill
Rodolfo Werner
Steve Forrest
Helena Herr
Ryan Reisinger
Javier A. Arata

<u>Report Date</u>:

7 October 2022

Table of contents

Executive Summary and Recommendations

All ARK vessels complied with the VRZs in austral summer 2021/22 but one vessel caught 166.7 tonnes of krill in the newly established Hope Bay VRZ in austral winter 2022. The EP recommends that the RP should (a) remind vessel operators of the importance of full compliance, and (b) advise operators to implement procedures which achieve full compliance.

As in previous years, Chinese vessels did not provide haul-by-haul data. The EP notes that the ARK commitment does not include a specific requirement to provide such data. The EP therefore recommends that the RP clarifies its expectations about what data fishing companies should report to the EP.

An initial analysis of recent changes in fishing patterns suggests that the implementation of the VRZs was associated with a shift in summer fishing out of Subarea 48.1, which contributed to increased summer catches in Subarea 48.2 and increased winter catches in Subarea 48.1, particularly in the Bransfield Strait outside the seasonal VRZs. Catches and effort in Subarea 48.1 have become more spatially concentrated over time, and it is possible that the VRZs have accentuated this pattern. The ecological effects of concentrated fishing are still poorly understood. This highlights the need for krill biomass estimates that are concurrent with fishing operations to properly assess localized krill depletion.

New research provides more information on environmental factors affecting krill distribution and how this distribution has changed over the decades. This information is useful for developing robust spatial management measures, including MPAs, to provide protection for krill and krill predators in a changing climate.

New published work on chinstrap penguins suggests that most summer foraging activity is within 50km of the coast, indicating that the current VRZs are effective at minimising fishery overlap with this species during the offspring rearing season. Collection and release of MAPPD data on penguin colony sizes have been severely disrupted by the Covid-19 pandemic and there were no new data available to analyse this year. This illustrates the need to develop a more robust penguin data collection regime to support the VRZs and implementation of an MPA.

Evidence of population increases in humpback and fin whales and improved understanding of consumption rates suggest that overall krill consumption by baleen whales in Subareas 48.1 and 48.2 is higher than previously thought. New research provides more evidence of spatial and temporal overlap between the fishery and foraging locations of large whales and fur seals. Other research shows an ongoing decline in the fur seal population in the South Shetland Islands which has been attributed to a combination of leopard seal predation and potentially worsening summer foraging conditions. These recent studies highlight the vulnerable nature of the ecosystem in Subarea 48.1. While the VRZs protect nearshore foraging habitats of marine mammals, they do not protect the whole foraging habitat, which includes, and for some species (e.g. for fin whales) is restricted to, offshore areas. This again highlights the need for better information on localized krill depletion by the fishery in offshore areas.

A recent publication on the VRZs is largely supportive of these buffer areas but identifies an urgent need for a credible data collection regime to support the development of improved krill fishery management procedures and the establishment of an MPA. The forthcoming 5-year review of the VRZs is an opportunity for the industry and other VRZ proponents to define data collection requirements and develop an appropriate data collection regime through proactive engagement with the wider community, including the ARK Science Industry Forum. The EP recommends an initial meeting between the RP and the EP, before the end of 2022, to clarify the objectives of the ARK Commitment in order to identify data collection priorities. The EP has made some suggestions about data collection priorities in this report (i.e., krill surveys concurrent with fishing operations and robust penguin colony monitoring).

The approach developed within CCAMLR to evaluate spatial management options on the basis of spatial overlap between krill, its predators and the fishery offers a low-cost, initial evaluation of the ecological benefits of the VRZs. We recommend that the RP identifies a way to fund this work.

CCAMLR working groups have made some progress towards an interim replacement for CM 51-07 in Subarea 48.1 but it is unclear what will be agreed at the October/November CCAMLR meetings. The EP reiterates its previous advice that, in the event that CM 51-07 expires with no replacement, ARK operators should limit catches in Subarea 48.1 to the consensus limit stated in CM 51-07 (155,000t yr^{-1}) until such time as CCAMLR agrees to a new limit.

Report from the Expert Panel (EP) on the evaluation of the ARK VRZ commitment during the 2021/22 fishing season

1. Introduction

This is the fourth annual report of the Expert Panel (EP) on the evaluation of the ARK VRZ commitment. The membership and chair of the EP have changed since the previous report (Appendix 1). The EP met online between July and September 2022. This year's outputs include new text explaining the EP's understanding of their role in the ARK VRZ process (Appendix 2). This text lists the information and advice that the EP is equipped to provide. The structure of the current report follows this list, with main text sections 3-9 providing brief text on each of the points raised in the list. A series of appendices provide more detailed information on some of these topics.

2. Compliance and fishing vessel operations

A total of nine vessels participated in the krill fishery during the 2021/2022 fishing season, all of which were affiliated with ARK. A total of 142,704 tonnes were caught in Subarea 48.1 between 26 March and 25 June 2022, representing 92.1% of the catch limit for that Subarea specified in CCAMLR Conservation Measure 51-07 (155,00 tonnes). All vessels complied with the austral summer VRZs (October 2021 - February 2022). However, one fishing vessel entered the year-round Hope Bay VRZ on 3 April 2022. The vessel fished up to 1.8 nm inside this VRZ before turning around, catching a total of 166.7 tonnes (0.15% of the season's catch) before exiting (Fig. 1).

The company involved provided the following statement: "*The Captain of the vessel made a misjudgement during fishing operations and consequently harvested krill within the outer margins of the Hope Bay no-take zone on 3 April. This was not intentional from the vessel master and can be attributed to a lack of awareness of the limits of the no-take zone at the time*".

The EP notes that full compliance is necessary for the successful operation of the VRZs and that crew awareness of VRZ boundaries is necessary for compliance. The EP advises operators to implement procedures to achieve full compliance, including through increasing crew awareness.

As in previous years, all Chinese vessels did not provide haul-by-haul data for analysis. The EP notes that the ARK Commitment does not include a specific requirement to provide such data. The EP therefore recommends that the RP clarifies its expectations about what data fishing companies should report to the EP.

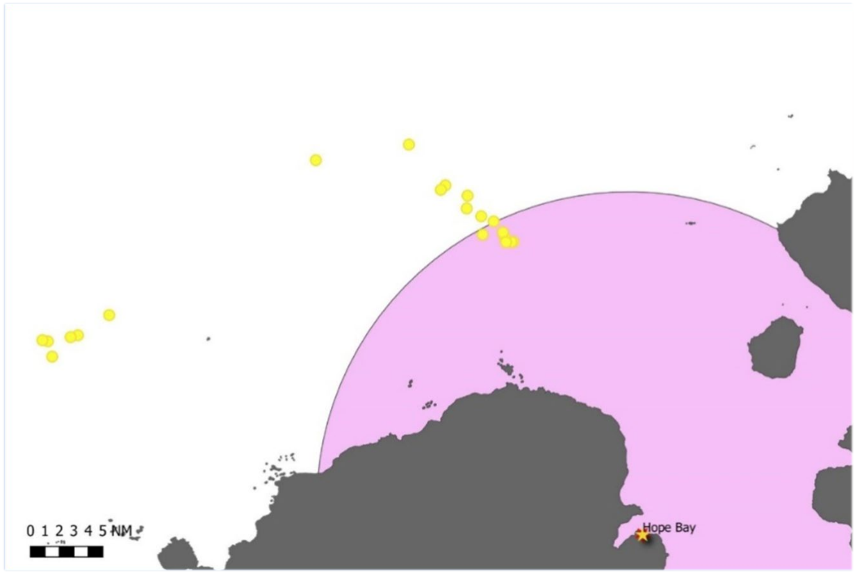


Figure 1. Distribution of fishing hauls conducted by a single fishing vessel around and inside Hope Bay VRZ during 2-4 April 2022.

Effect of the VRZ on fishing patterns

The initial implementation of the VRZs in the 2019 fishing season generated or accentuated changes in the distribution of catches by the fleet. Currently, the fleet starts the season in Subarea 48.2 and moves to Subarea 48.1 by mid-late March. This has resulted in a significant increase of catches in Subarea 48.2 during summer and, conversely, a significant reduction in Subarea 48.1, due to the cessation of fishing inside VRZs in summer. During winter, catches in Subarea 48.1 have increased since the implementation of the VRZs. Notably, this increase in winter catches is concentrated in the Bransfield Strait, outside of the VRZs, even though the VRZs are open to fishing in the winter.

The implementation of the VRZs may also be involved in an increasing concentration of catches within a few small spatial units, SUs (30km-hexagons). Catch density and fishing effort, two measures of the fishery footprint, are low for the whole area fished but most catch occurs in relatively few SUs in each Subarea (Fig. 2). Two SUs in the Bransfield Strait and one SU in Gerlache Strait had catches > 20 ton/km^2 (range: 20.9 – 50.3 ton/km^2) in about half the seasons analyzed (2013-2022) (Fig. 3). Catch density has increased in Bransfield Strait, but not Gerlache Strait, since the implementation of the VRZs.

In Subarea 48.2, the fishery footprint is also low except at two SUs, where catches have ranged between 20.5-88.3 ton/km^2 every season since 2017. This pattern has become more pronounced since the implementation of the VRZs (Fig. 4). The high catch density recorded at these SUs is similar to or lower than the long-term krill density estimated for krill in each region (34.19 g/m^2 (n = 30) and 58.53 g/m^2 (n = 1) for Bransfield and Gerlache Strait, respectively (WG-EMM-2022). However, the scarce data available for winter suggest that krill density in Bransfield Strait could reach ~228 g/m^2 (Reiss et al., 2017). Similarly, krill density estimates in the northern area of the South Orkneys indicate an average of 109.3 g/m^2 (range: 10.1 – 301.4 g/m^2) (Krafft et al., 2018), higher than catch densities observed at the above-mentioned SUs.

The fleet seeks hotspots with higher than the average krill concentration; thus, it is likely that krill densities were higher than average when high catch densities were achieved. In addition, catches were obtained over a period of 1 to 2 months, which could allow for some influx of krill. Nonetheless, carrying out krill surveys concurrent with the fishery (particularly in Subarea 48.1) is urgently needed to assess the localized catch rate of the fishery properly.

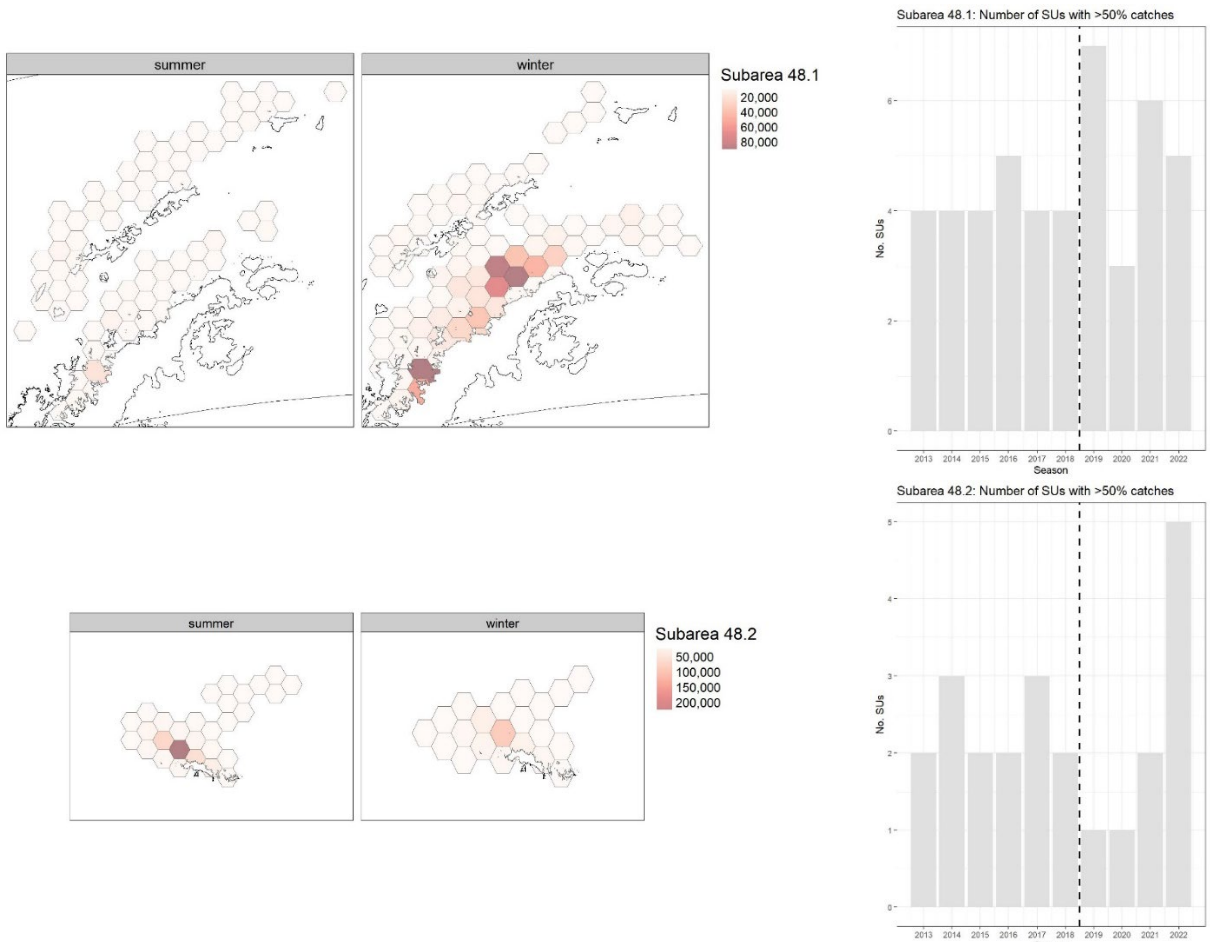


Figure 2. Distribution (left) of SUs containing 90% of krill catches, and number of SUs (right) containing >50% of krill catches during seasons 2012/13 to 2021/22. Catch per SU (*left*) represents the sum of catches (tonnes) between the 2013-2022 seasons. Source: ARK database.

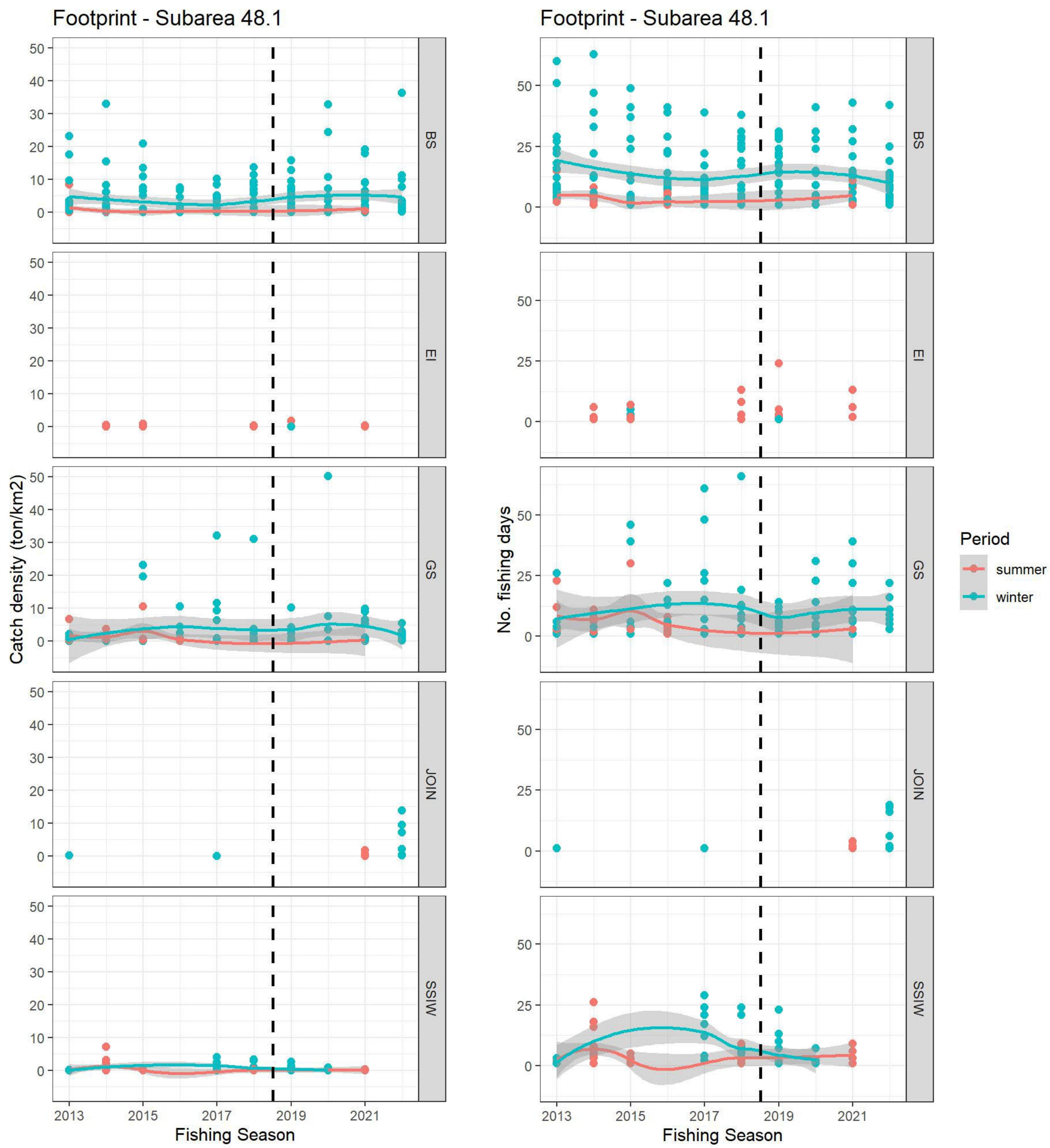


Figure 3. Footprint by strata in Subarea 48.1 for SUs from which 90% of the annual catch is taken. Vertical dashed line: implementation of the VRZs. Source: ARK database.

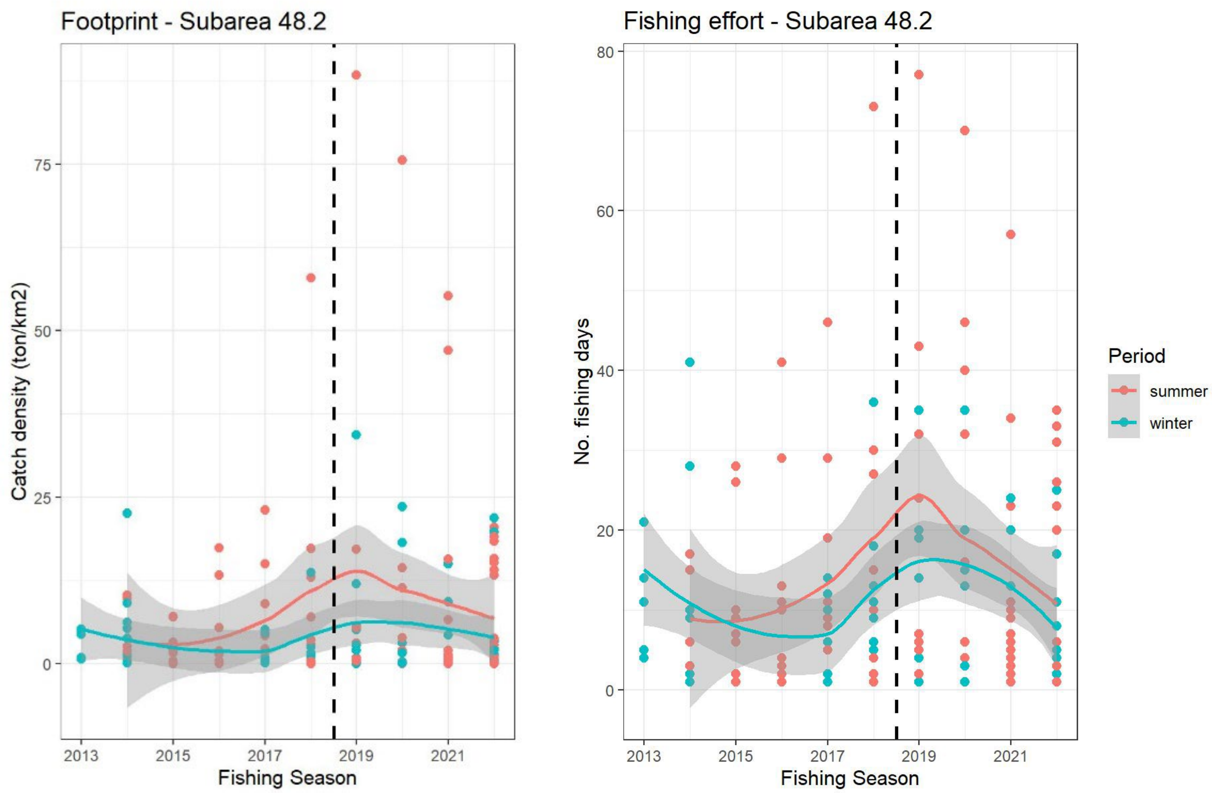


Figure 4. Footprint Subarea 48.2 for SUs from which 90% of the annual catch is taken. Vertical dashed line: implementation of the VRZs. Source: ARK database.

3. Krill

The Expert Panel has previously reported on the difficulties of assessing change in the krill population based on current data streams and the lack of any new data or analysis designed to assess the effects of the ARK Commitment. This situation remains unchanged, and there is therefore no basis for concluding whether the VRZs have a positive or negative effect on the availability of krill to predators compared to areas open to fishing all year round.

Relevant recent publications include a statistical model of krill spatial distribution in Subarea 48.1 (Warwick-Evans et al., 2022a) and further analysis of long-term changes in krill distribution across Subareas 48.1 to 48.3 (Atkinson et al., 2021). These papers provide insight into the environmental factors that influence krill distribution and how these relationships change over time. Such information is necessary for designing MPAs that protect krill now and into the future. Watters and Hinke (2022) show that, over the past decade, fishing effort and catch have become more concentrated in space and time in Subarea 48.1. In Subarea 48.2 the spatial distribution of effort remained relatively stable over the same time period but catch, and therefore the spatial concentration of catch, has more than doubled. This concentration has occurred while Conservation Measure 51-07 has been in force, capping the Subarea 48.1 catch limit at 155,000 tonnes (see section 6), and Watters and Hinke (2022) argue that "*CM 51-07 is imperfect but good enough*."

4. Penguins

Penguin population trends

Renewed field activity allowed a resumption of penguin census work for the field season 2021-2022. This work included censuses in Subarea 48.1 (Hart et al., *pers. comm.*), the Weddell Sea (Lynch et al., *pers. comm.*), and late season efforts in Subarea 48.1 (Naveen et al., *pers. comm.*), as well as local efforts by various research station scientists. Since the 2019-20 field season few records have been uploaded to MAPPD (Humphries et al., 2017) largely due to pandemic-related and other shortfalls, so it is not possible to provide an update on penguin population trends. The EP has previously noted the limitations of opportunistic data collection to address specific questions about predator impacts related to krill harvest. This issue is highlighted by the disruption to MAPPD data collection and reporting over several years and illustrates the need to develop a more robust penguin data collection regime to support the monitoring of the VRZs and the implementation of an MPA.

Evidence for adequacy of VRZ buffer dimensions.

Clucas et al. (2022) reviewed the South Georgia and the South Sandwich Islands (SGSSI) Marine Protected Area (MPA). They found that breeding chinstraps collectively consume 5,300 tons of krill per day during the brood stage, and 4,400 tons during the crèche phase. They estimated that 258,000 tons of krill are required to sustain parenting adults over the chick-tending period in that area. The study found that the birds made foraging trips with an average maximum distance travelled from the colony of 28.9 kilometers, with few trips exceeding 50 kilometers. They contrasted this with other studies on chinstraps where trips during the chick-rearing period extend 40–70 km from the colony on average, with 42 km average maximum distance (Lowther et al., 2018; Trathan et al., 2018; Warwick-Evans et al., 2018; Phillips et al., 2021). The authors postulate that the shorter foraging range in the South Sandwich Islands may (partially) be the result of differences in bathymetric topography. Subarea 48.4 (allocated a catch limit of 93,000 tons under Conservation Measure 51-07) is closed to fishing within 50 kilometers of each of the islands. The authors found that the preferred foraging habitat of chinstrap penguins, calculated from tracking and habitat modelling, "...*aligns well with the 50 km pelagic no-take zone around the islands*"

A second analysis, based on combined telemetry data from 1999 onward, found that for Subarea 48.1 the "*probability of occurrence* [of observed foraging distance from colonies during incubation and chick rearing] *was greater than 0.5 within 36, 41, and 13 km of the colony for chinstraps, Adélie, and gentoo penguins, respectively*." "*Krill consumption is particularly high in locations proximate to large penguin breeding colonies across the South Shetland Islands and at the tip of the Antarctic Peninsula*" (Warwick-Evans et al., 2022b). As noted elsewhere in this report, this inshore foraging habitat is shared with whales, which have not been included in many analyses regarding krill consumption by predators and the fishery.

Non-breeding penguins

While the extent of the VRZs is based on the foraging ranges of breeding penguins, a significant portion of every penguin population is non-breeding (e.g., immature birds or birds that lose their nests early in the breeding season). Non-breeding Adelie penguins on the Western Antarctic

Peninsula (primarily Subarea 48.1) were telemetered and their movements compared to those of breeding birds (which seldom moved >40 km). During incubation, non-breeder foraging territory was similar to breeders, but during provisioning and creche non-breeders spent significant time transiting the Bransfield Strait instead and frequently moved into the Weddell Sea on foraging bouts, returning to breeding colonies from time to time (Oosthuizen et al., 2022). These results indicate that part of the Adelie penguin population uses areas outside the VRZs during the breeding season. Thus, the VRZs do not fully protect penguin populations during the breeding season and may redirect fishing effort to habitats that are used by parts of these populations (the non-breeders).

5. Other predators

Warwick Evans et al. (2022b) show that the krill consumption of 3 penguin, 11 flying bird, 1 pinniped and 2 whale species is spatially concentrated at small scales, often close to penguin breeding colonies in near shore areas. The authors draw attention to the fact that currently many krill predator species are not considered in krill fishery management. They argue that precautionary krill fishery management requires additional abundance and consumption estimates for pack-ice seals, finfish, squid, and other baleen whale species currently not considered.

Marine mammals

Humpback whale abundance in CCAMLR Subarea 48.2 is estimated to be relatively low (785 individuals, 95% CI = 208−2960) compared to Subareas 48.3 (12,103, 95% CI = 7145−20,499), 48.4 (11,656, 95% CI = 5865−23,164) (Baines et al., 2021) and Subarea 48.1 (19,107) (Johannessen et al., 2022). Total krill consumption by humpback whales in the Antarctic Peninsula region (Subarea 48.1) is estimated to be 1.4-3.7 million tons (Johannessen et al., 2022), but consumption rates may actually be three times higher (Savoca et al., 2021). In the Antarctic Peninsula region, spatiotemporal overlap between minke and humpback whales, and the krill fishery, is predicted to be highest later in the season, from March to May, peaking in April, and localised, particularly in the Bransfield Strait and Gerlache Strait (Johannessen et al., 2022; Reisinger et al., 2022), raising concerns about local krill depletion (Reisinger et al., 2022).

Fin whale abundance around Elephant Island and the South Shetland Islands (in Subarea 48.1) was estimated at 7909 individuals (95% CI 1047–15,743) during summer, with regular occurrence of large feeding aggregations of up to 150 animals, pointing to a recovery of fin whales and an increase in population numbers (Herr et al., 2022).

The predicted foraging habitat for juvenile and subadult male Antarctic fur seals tracked from the South Shetland Islands is centred on waters off the Western Antarctic Peninsula and in the Scotia Sea during winter (March et al., 2021). Since 2007, Antarctic fur seal numbers in the South Shetland Islands have declined by 86%, mainly due to leopard seal predation, and a potential reduction in prey (krill and fish availability) (Krause et al., 2022).

6. Fishery management

The Antarctic krill fishery in Subarea 48.1 is managed by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). At present the main regulations affecting the catch and spatial operation of the fishery are Conservation Measure (CM) 51-01 which defines the 620,000 t yr^{-1} effective catch limit (“trigger level”) for Subareas 48.1 to 48.4, and CM 51-07 which caps the catch that can be taken in each of these subareas. The cap for Subarea 48.1 is 155,000 t yr^{-1}. In addition to direct management of fisheries using area-specific catch limits, CCAMLR also aims to develop a representative system of Marine Protected Areas (MPAs) in the Southern Ocean. Each implemented MPA is likely to have its own unique set of objectives, which will determine how it affects fisheries. A proposal for an MPA in parts of Subareas 48.1 and 48.2 has been developed and refined with input from CCAMLR’s scientific working groups, but there has been no progress in the 2022 intersessional period towards the implementation of an MPA in Subarea 48.1.

In 2022 the CCAMLR Scientific Committee and its working groups continued working on a revised direct management approach for Antarctic krill. This approach is intended to include regular estimates of krill biomass from acoustic surveys, computation of precautionary harvest rates (the proportion of biomass that can be harvested in each fishing season) using a krill population model, and spatial distribution of catches based on analyses of spatial overlap between krill, its predators and the fishery.

CM 51-07 was due to expire at the end of the 2020/21 fishing season but was extended until the end of the 2021/22 season to allow progress on an interim implementation of the revised approach for Subarea 48.1. Progress was made during WG-ASAM and WG-EMM 2022 on agreeing biomass estimates and spatial catch distributions for Subarea 48.1. This progress suggests that any interim measure for Subarea 48.1 is likely to be based on six or seven spatial units, which do not distinguish areas inside and outside of the VRZs.

Less progress was made on agreeing on the model inputs required to compute precautionary harvest rates. Further discussions will take place at WG-FSA in October 2022. At the time of writing, it is not possible to predict the outcome of the 2022 CCAMLR meetings in terms of krill fishery management for Subarea 48.1. The EP considered the following three scenarios**:**

Scenario one: CM 51-07, in its current form, is extended for at least another year. In this case, ARK operators will be obliged to continue to comply with CM 51-07.

Scenario two: CCAMLR produces a new Conservation Measure specifying evidence-based spatially-resolved catch limits for Subarea 48.1. In this case, ARK operators will be obliged to comply with the new Conservation Measure.

Scenario three: CM 51-07 expires with no replacement and no consensus advice on appropriate spatially-resolved catch limits. In this case, ARK operators should limit catch in each Subarea to the consensus limits stated in CM 51-07 (155,000 t yr^{-1} in Subarea 48.1; 279,000t yr^{-1} in each of Subareas 48.2 and 48.3; 93,000 t yr^{-1} in Subarea 48.4) until such time as consensus advice is available.

Scenario four: The CCAMLR Scientific Committee provides consensus advice on appropriate spatially-resolved catch limits for krill in Subarea 48.1 but this advice is not accepted by the Commission. In this case, ARK operators should follow the advice of the Scientific

Committee if they are able to do so without breaching any Conservation Measures in force or the ARK Commitment.

In any case, ARK operators are obliged to comply with all Conservation Measures in force and expected to continue to comply with the ARK Commitment which, in its current form, is valid until 1st January 2024.

7. Response to requests from the RP

There were no requests received from the RP this year.

8. Additional information and advice relevant to the RP

Spatial overlap analysis

The approach developed within CCAMLR to assess the spatial overlap between krill, its predators and the fishery provides a framework for comparing spatial management approaches in terms of metrics that have been accepted within CCAMLR. These metrics include measures of the overlap distribution between spatial areas, where a low value indicates a more even distribution of catch relative to krill distribution, predator demand (and, in one version of the measure, previous catch distribution). A study presented to CCAMLR used this method to evaluate the VRZs under a specific scenario (Warwick Evans & Trathan 2021). In this scenario, there are four separate VRZs and a single homogenous area outside the VRZs (Fig.5). The entire summer catch is allocated to the area outside the VRZs and the winter catch is allocated between spatial units according to the formula:

$$\alpha_{a,p} = ((1- r_{a,p}) * c_{a,p} * Z_{a,p} * K_{a,p} * A_{a,p}) / \sum_{a',p'} (1 - r_{a,p}) * c_{a,p} * Z_{a,p} * K_{a,p} * A_{a,p}$$

where r is a measure of predator demand in area a during season (summer or winter) p, c is a fraction of the long-term average Subarea catch (indicating fishery demand), Z is a proportion of annual catch (indicating the split between seasons), K is krill density, A is area (km^2) and $\sum_{a',p'}$ indicates the sum across all areas and seasons.

In this analysis, the performance of ARK VRZs was similar to that of an alternative option based on six spatial strata, which is preferred within CCAMLR's scientific working groups. However, in the view of the EP, the analysis could be refined to provide a more thorough evaluation of the VRZs. A key refinement is to evaluate a hybrid scenario including VRZs and the six spatial strata currently being considered by CCAMLR's scientific working groups.

This spatial overlap analysis is a low-cost, first step towards evaluating the ecological benefits of the VRZs. The EP recommends that the RP identifies a way to fund this work.

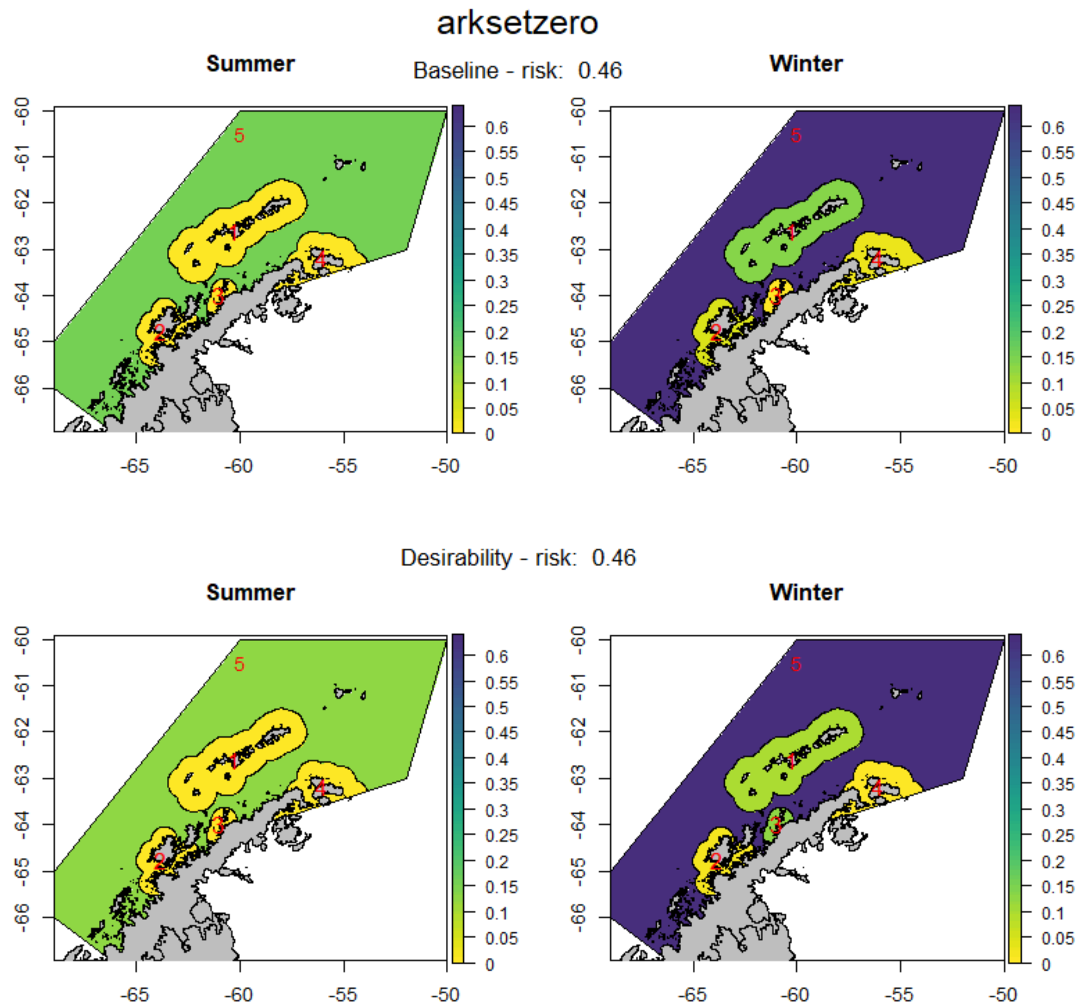


Figure 5. Results of spatial overlap analysis applied to a scenario representing the VRZs. Colours indicate the proportion of catch allocated to each spatial unit. “Baseline risk” measures the overlap between catch, predation pressure and juvenile krill distribution. “Desirability risk” is an adjusted measure which takes into account the previous spatial distribution of catches.

New publication on VRZs

A new journal article about the VRZs, with the title “Voluntary actions by the Antarctic krill fishing industry help reduce potential negative impacts on land-based marine predators during breeding, highlighting the need for CCAMLR action” was published in 2022 by Olav Rune Godø, former chair of the EP, and Philip Trathan (Godø and Trathan 2022).

The article summarises the rationale for the establishment and the objectives of the VRZs as follows: "*Talks between ARK and the NGOs (initiated by Greenpeace), led to an agreement on the establishment of a set of precautionary voluntary measures. These voluntary measures include spatial-temporal restrictions on the operation of krill fishing in order to mitigate any potential negative impacts on the life history processes (e.g., foraging, reproduction, and survival) of land-based predators during their breeding season*."

The article provides limited technical detail about the process used to delineate the VRZs. This process used penguin breeding site locations reported in Humphries et al. (2017), with proposed buffers initially based on the weighted mean maximum foraging distance during chick rearing of dominant penguin species (either Adelie, Chinstrap or Gentoo), although "*in discussions with ARK, the buffers were constrained to less than this mean maximum foraging range as the distribution of penguin foraging trips is generally skewed*."

The article cites positive and negative stakeholder opinions of the VRZs (Table 1) but is itself generally positive, claiming that the VRZs have "*reduced potential competitive effects on krill-dependent predators in Subarea 48.1*". In particular the article indicates that if CM 51-07 expires without replacement, then the VRZs "…*will be the only regulation providing precautionary protection at relevant spatial and temporal scales*".

Nonetheless, the article identifies issues with the current implementation of the VRZs and suggests some priorities for improvement. In particular the article recommends that:

"*ARK, as a matter of urgency, should consider extending the voluntary buffers to include the areas around Elephant Island and around the South Orkney Islands*". In addition, a data collection regime should be organized around "research zones" that are open to fishing and contrast with unfished VRZs and "climate change reference areas" located upstream of any krill harvesting.

Table 1: Positive and negative stakeholder comments about the ARK Commitment and VRZs cited by Godø and Trathan (2022).

Positive	**Negative**
The ARK Commitment will…	
… demonstrates stakeholders can agree on a way forward	*… has no grounding in science*
…creates new possibilities to collect information about fisheries impacts and krill dynamics if sampling protocols can also be agreed	*… will undermine the development of a scientifically based MPA*
…could be part of an experiment, whereby some areas are exploited while other comparable areas are used as reference areas to help disentangle confounding drivers of change, for example climate change and krill fishing	*… will lead to greater complexity for the (CCAMLR) Commission*

The EP notes that the explanation of the basis for the buffer zones provided by Godø and Trathan (2022) is vague. It would be helpful if participants in the "*discussions with ARK"* could specify what the chosen VRZ distances represent beyond simply being "*less than this mean maximum foraging range"*. The EP further notes that two of the three positive stakeholder comments in Table 1 concern the potential of the ARK Commitment to deliver information about how fishing affects the krill-centered ecosystem but that such information remains to be delivered. The EP supports the call for the development of a credible data collection regime. The 5-year review of the VRZs in 2023 is an opportunity for the industry and other VRZ proponents to define data collection requirements and develop an appropriate data collection regime through proactive engagement with the wider community, including the ARK Science Industry Forum. The EP recommends an initial meeting between the RP and the EP, before the end of 2022, to clarify the objectives of the ARK Commitment in order to identify data collection priorities.

9. References

Atkinson, A., Hill, S. L., Reiss, C. S., Pakhomov, E. A., Beaugrand, G., Tarling, G. A., Yang, G., Steinberg, D. K., Schmidt, K., Edwards, M., Rombolá, E., and Perry, F. A.2021. Stepping stones towards Antarctica: Switch to southern spawning grounds explains an abrupt range shift in krill. Global Change Biology, 28:1359-1375. https://doi.org/10.1111/gcb.16009

Baines, M., Kelly, N., Reichelt, M., Lacey, C., Pinder, S., Fielding, S., Murphy, E., Trathan, P., Biuw, M., Lindstrøm, U., Krafft, B. A., and Jackson, J. A. 2021. Population abundance of recovering humpback whales Megaptera novaeangliae and other baleen whales in the Scotia Arc, South Atlantic. Marine Ecology Progress Series, 676:77-94. https://doi.org/10.3354/meps13849

Clucas, G. V., Warwick-Evans, V., Hart, T., and Trathan, P. N. 2022. Using habitat models for chinstrap penguins, *Pygoscelis antarctica,* to inform marine spatial management around the South Sandwich Islands during the penguin breeding season. Deep Sea Research Part II: Topical Studies in Oceanography, 199:105093. doi: 10.1016/j.dsr2.2022.105093

Godø, O. R., and Trathan, P. N. 2022. Voluntary actions by the Antarctic krill fishing industry help reduce potential negative impacts on land-based marine predators during breeding, highlighting the need for CCAMLR action. ICES Journal of Marine Science, 79:1457-1466. https://doi.org/10.1093/icesjms/fsac092

Herr, H., Viquerat, S., Devas, F., Lees, A., Wells, L., Gregory, B., Giffords, T., Beecham, D., and Meyer, B. 2022. Return of large fin whale feeding aggregations to historical whaling grounds in the Southern Ocean. Sci Rep, 12(1):9458. https://doi.org/10.1038/s41598-022-13798-7

Humphries, G., Naveen, R., Schwaller, M., Che-Castaldo, C., McDowall, P., Schrimpf, M., and Lynch, H. 2017. Mapping Application for Penguin Populations and Projected Dynamics (MAPPPD): Data and tools for dynamic management and decision support. Polar Record, 53(2):160-166. Doi:10.1017/S0032247417000055

Johannessen, J. E. D., Biuw, M., Lindstrom, U., Ollus, V. M. S., Martin Lopez, L. M., Gkikopoulou, K. C., Oosthuizen, W. C., and Lowther, A. 2022. Intra-season variations in distribution and abundance of humpback whales in the West Antarctic Peninsula using cruise vessels as opportunistic platforms. Ecol Evol, 12(2):e8571. https://doi.org/10.1002/ece3.8571

Krause, D. J., Bonin, C. A., Goebel, M. E., Reiss, C. S., and Watters, G. M. 2022. The Rapid Population Collapse of a Key Marine Predator in the Northern Antarctic Peninsula Endangers Genetic Diversity and Resilience to Climate Change. Frontiers in Marine Science, 8. https://doi.org/10.3389/fmars.2021.796488

Lowther, A. D., Trathan, P. N., Tarroux, A., Lydersen, C., and Kovacs, K. M. 2018. The relationship between coastal weather and foraging behaviour of chinstrap penguins, *Pygoscelis antarctica*. ICES Journal of Marine Science, 75(6):1940-1948. https://doi.org/10.1093/icesjms/fsy061

March, D., Drago, M., Gazo, M., Parga, M., Rita, D., and Cardona, L. 2021. Winter distribution of juvenile and sub-adult male Antarctic fur seals (*Arctocephalus gazella*) along the western Antarctic Peninsula. Sci Rep, 11(1):22234. https://doi.org/10.1038/s41598-021-01700-w

Oosthuizen, W. Chris, Pierre A. Pistorius, Malgorzata Korczak-Abshire, Jefferson T. Hinke, Mercedes Santos, and Andrew D. Lowther. 2022. The Foraging Behavior of Nonbreeding Adélie Penguins in the Western Antarctic Peninsula during the Breeding Season. Ecosphere 13(5):e4090. https://doi.org/10.1002/ ecs2.4090

Phillips, J. A., Fayet, A. L., Guilford, T., Manco, F., Warwick-Evans, V., and Trathan, P. 2021. Foraging conditions for breeding penguins improve with distance from colony and progression of the breeding season at the South Orkney Islands. Movement Ecology, 9:22. https://doi.org/10.1186/s40462-021-00261-x

Reisinger, R. R., Trathan, P. N., Johnson, C. M., Joyce, T. W., Durban, J. W., Pitman, R. L., and Friedlaender, A. S.2022. Spatiotemporal Overlap of Baleen Whales and Krill Fisheries in the Western Antarctic Peninsula Region. Frontiers in Marine Science, 9. https://doi.org/10.3389/fmars.2022.914726

Savoca, M. S., Czapanskiy, M. F., Kahane-Rapport, S. R., Gough, W. T., Fahlbusch, J. A., Bierlich, K. C., Segre, P. S., Di Clemente, J., Penry, G. S., Wiley, D. N., Calambokidis, J., Nowacek, D. P., Johnston, D. W., Pyenson, N. D., Friedlaender, A. S., Hazen, E. L., and Goldbogen, J. A. 2021. Baleen whale prey consumption based on high-resolution foraging measurements. Nature, 599(7883):85-90. https://doi.org/10.1038/s41586-021-03991-5

Trathan, P. N., Warwick-Evans, V., Hinke, J. T., Young, E. F., Murphy, E. J., Carneiro, A. P. B., Dias, M. P., Kovacs, K. M., Lowther, A. D., Godø, O. R., Kokubun, N., Kim, J. H., Takahashi, A., and Santos, M. 2018. Managing fishery development in sensitive ecosystems: identifying penguin habitat use to direct management in Antarctica. Ecosphere 9(8):e02392. Doi: 10.1002/ecs2.2392

Warwick-Evans, V., Fielding, S., Reiss, C. S., Watters, G. M., and Trathan, P. N. 2022a. Estimating the average distribution of Antarctic krill *Euphausia superba* at the northern Antarctic Peninsula during austral summer and winter. Polar Biology, 45:857-871. doi: 10.1007/s00300-022-03039-y

Warwick-Evans, V., Kelly, N., Dalla Rosa, L., Friedlaender, A., Hinke, J. T., Kim, J. H., Kokubun, N., Santora, J. A., Secchi, E. R., Seyboth, E., andTrathan, P. N. 2022b. Using seabird and whale distribution models to estimate spatial consumption of krill to inform fishery management. Ecosphere, 13(6). https://doi.org/10.1002/ecs2.4083

Warwick-Evans, V., Ratcliffe, N., Lowther, A., Manco, F., Ireland, L., Clewlow, H. L., and Trathan, P. N. 2018. Using habitat models for chinstrap penguins *Pygoscelis antarctica* to advise krill fisheries management during the penguin breeding season. Diversity and Distributions, 24:1756-1771. https://doi.org/10.1111/ddi.12817

Warwick-Evans, V., and Trathan, P. N. 2021. Using the Risk Assessment Framework to spread the catch limit in Subarea 48.1. WG-FSA-2021/16.

Watters,G. M., and Hinke, J. T. 2022. Conservation in the Scotia Sea in light of expiring regulations and disrupted negotiations. Conservation Biology, e13925. https://doi.org/10.1111/cobi.13925

WG-EMM-2022. Report of the Working Group on Ecosystem Monitoring and Management, Virtual meeting, 4 to 11 July 2022.

Appendix 1. Expert panel membership

Name (role) and affiliation		Key author of sections
Simeon Hill (Chair) British Antarctic Survey, UK		Summary, Introduction, Krill, Fishery Management, Additional information and advice relevant to the RP
Rodolfo Werner Senior Advisor of The Pew Charitable Trusts and Antarctic and Southern Ocean Coalition		Summary, Additional information and advice relevant to the RP
Steve Forrest Research Associate of the Antarctic Site Inventory (Oceanites Inc.), USA		Summary, Penguins
Helena Herr University of Hamburg, Germany		Summary, Other Predators
Ryan Reisinger University of Southampton, UK		Summary, Other Predators
Javier A. Arata (Secretary) Executive Officer of ARK		Summary, Compliance and fishing vessel operations

Appendix 2. Expert Panel remit

The text below summarises the Expert Panel's understanding of their role in the VRZ review process.

The ARK Voluntary Restricted Zones (VRZs) were established through negotiation between fishing companies and nongovernmental organisations in 2018. The stated goal was to "get an MPA in Domain 1 adopted by the CCAMLR Commission, recognizing the industry's role in contributing to the long term ambition for a large scale network of MPAs in the Antarctic Ocean."[1] There is no documentation of any scientific rationale for the VRZs and no statement of how the VRZs will be used to achieve the goal of a large scale network of MPAs. Similarly, there is no statement of the conservation objectives of the VRZs and no documented process for assessing their effectiveness.

Nonetheless, the VRZs reflect the known foraging locations of various penguin species and the summer exclusion period covers the penguin chick rearing period. The VRZs are broadly similar to other measures that restrict krill fishing close to land. These measures include (i) CCAMLR's Conservation Measure 51-04 governing exploratory krill fisheries. This states that "no more than 75% of the catch limit shall be taken within 60 n miles of known breeding colonies of land-based krill-dependent predators"[2], and (ii) the South Georgia and South Sandwich Islands no take zones, which extend 30 km and 50 km from the shore respectively[3].

The siting of the VRZs reflects widespread support for limiting krill fishing close to colonies of land-based predators (especially penguins). This siting prioritises protection of the life-stages of land-based predators that rely on foraging close to shore over the wider suite of life-stages and species that might be affected by krill fishing. Despite this, some penguin colonies, including those on Elephant Island and in parts of the Bransfield Strait are not included in VRZs. The Expert Panel (EP) was established in 2019, after the implementation of the VRZs, to provide advice to a Review Panel (RP) conducting annual reviews of the VRZs. The purpose of this review is stated in the ARK commitment document[1] and the Terms of Reference (TORs) of the EP are stated in its first annual report[4]. The EP has provided feedback on these TORs. The purpose of the current text is to summarise the structure and working method of EP and clarify the scope of its contribution to annual reviews.

The EP currently consists of seven members, six of whom contributed to the 2022 report. The combined expertise of the EP covers Antarctic krill and some of its predators (especially penguins and baleen whales) as well as CCAMLR and its approach to conservation. The members include a Chair and a Secretary. The Chair's role is to lead the work of the EP and present its annual report to the RP. The Chair is elected by members of the panel to serve a three-year term. The ARK Executive Officer serves as Secretary, a role that includes organising and minuting meetings. With the exception of the ARK Executive Officer, the members of the EP provide their input on a voluntary basis. Replacement members will be selected by serving members of the EP when necessary.

---

[1] https://static1.squarespace.com/static/5df7d7d764f21960e325dbb4/t/6082e32150166565277327a5/1619190562009/ARK+Commitment+rev+DEC+2020.pdf
[2] https://cm.ccamlr.org/en/measure-51-04-2020
[3] https://www.gov.gs/32110-2/
[4] https://static1.squarespace.com/static/5df7d7d764f21960e325dbb4/t/5ebdab58072e9456916ffd30/1589488475129/EP+Report+2019+Executive+Summary.pdf

EP members are not provided with any additional resources to help in their work and the only data which has been supplied to date concerns the fishing locations and catches of most ARK member vessels. The limited time and resources available to the EP and the lack of documentation about the rationale for the VRZs constrains the scope of the advice that the EP can realistically provide. In particular, the EP is not able to establish the “conservation benefits” of the VRZs or provide a retrospective scientific rationale for them. The EP has, however, provided advice on the steps that would be necessary to define conservation objectives and monitor performance relative to these objectives[4,5]. Equally the EP cannot advise on “operational challenges” in complying with the VRZs.

The EP is able to contribute to the annual review process in the following ways:

(1) Analyse catch data to assess compliance with the VRZs.

(2) Report briefly on new data and research on the status of Antarctic krill and its predators in Subareas 48.1 and 48.2.

(3) Report briefly on developments in krill fishery management and ecosystem protection affecting Subareas 48.1 and 48.2.

(4) Provide expert opinion in response to clear requests from the RP.

(5) Provide advice on how the RP can progress its objectives when these are beyond the current capacity of the EP.

(6) Provide additional information or advice which the EP considers relevant to the work of the RP.

The delivery of these contributions will depend on the availability of relevant data. Under the current arrangements contribution 1 (compliance) is the only part of the annual review process for which the EP expects to perform any new quantitative analysis. Expert opinion will be provided with the general caveat that opinions are subjective.

[5]https://static1.squarespace.com/static/5df7d7d764f21960e325dbb4/t/605b8eafa44ec4206c7c2e4e/1616613039712/Report+Expert+Panel+2020+wvf.pdf

Appendix 3. Further fishery operations analysis

SEASONAL COMPLIANCE WITH VRZs DURING SEASON 2021/22

Dr J.A. Arata (ARK)

SUMMARY

- Nine krill fishing vessels operated in the 2021/22 season, all affiliated to ARK.
- Four out of the six companies affiliated with ARK, representing six vessels, provided haul-by-haul data.
- The information shows that the whole krill fishing fleet complied with the seasonal VRZ during the summer (December-February).
- By contrast, one vessel fished on 3 April 2022 inside the year-round VRZ at Hope Bay, catching 166.7 tonnes, or 0.15% of the total catch for the 2021/22 season.

INTRODUCTION

ARK Committed to several voluntary measures in 2018[6]. One of the most well-known is the Voluntary Restricted Zones (VRZs), implemented on 1 December 2018. VRZs are seasonal protection zones to safeguard breeding penguins. Under recommendation by the Review Panel, ARK implemented on 1 December 2020 a new, year-round VRZ around Hope Bay. This report analyses the compliance of ARK's krill fishing vessels with VRZs during the 2021/22 krill fishing season.

METHODS

Data Availability

Data used in this report was obtained from here different sources:

- 5-day catch reports submitted by the CCAMLR Secretary; these reports informed the total catch and number of vessels fishing on a 5-day period, and the total accumulated catch per Subarea.
- C1 data forms submitted by ARK members; these forms provide haul-by-haul information on location, effort and catch by individual vessels.
- Daily vessel distribution from the Marinetraffic.com portal; this portal provides access to the AIS position of all vessels registered.

[6]https://www.ark-krill.org/ark-voluntary-measures

Analyses

Haul-by-haul data from four ARK members, accounting for 6 vessels, were provided to the ARK database. Data was imported from Excel sheets and a preliminary cleaning was performed as follows: data with no catches were removed; hauls positions were filtered and corrected when obvious (i.e., -420.6 instead of -42.06), using positions for preceding/following 3 hauls; date mistakes were corrected when obvious. Clean data was processed as followed: haul distribution was estimated as the middle point between the start and end of each tow; distance between hauls was estimated and then data was filtered for speed estimates above 15 knots.

Data from December to February was assigned as "summer" and from March to June as "winter".

All analyses were run in R 4.2.0 (R Core Team 2022) under RStudio 2022.02.3 GNU. Packages used for analyses included the following: data manipulation: 'readr', 'openxlsx', 'dplyr', tidyverse'; spatial analysis: 'sf', 'sp', 'raster'; visualization: 'ggplot2', 'ggformula', 'tmap', 'rgeos', 'gridExtra'.

Spatial analyses were conducted using the South Pole Lambert Azimuthal Equal Area Projection, centred at longitude 50°W.

RESULTS

Krill Catches – CCAMLR reports

A total of nine vessels participated in the fishery this season. The season started in Subarea 48.2, with vessels joining the fishery from 1-5 December 2021 until 21-25 February 2022. The fleet continued fishing there until 26-31 March, when they moved to Subarea 48.1 (Fig. A3-1). The fleet fished in Subarea 48.1 up to 21-25 June, following CCAMLR's notification of fishery closure for Subarea 48.1 on 27 June, based on projected catches; however, the quota was not reached (Table A3-1). After the closure of Subarea 48.1, part of the fleet moved to Subarea 48.3, while the other fraction returned to Subarea 48.2, where it continued fishing until late July when sea ice closed access to the main fishing grounds (ARK information).

Distribution Pattern of the Fleet

The distribution of the fleet was described using (i) haul-by-haul data provided by the fishing companies and (ii) AIS positions obtained from www.MarineTraffic.com (Table A3-2).

AIS information

Daily position of vessels were obtained from MarineTraffic.com for all nine vessels participating in the fishery.

All vessels fished exclusively in Subarea 48.2 during the summer season, 1 December 2021 to 28 February 2022 (Fig. A3-2).

During the winter season (1 March to 30 June 2022), one vessel was identified as conducting fishing activities inside VRZ Hope Bay (Fig. A3-3).

Haul-by-haul data

Four companies affiliated with ARK, representing six vessels, provided haul-by-haul data (Table A3-2), which represented 100% and 79.91% of summer and winter data for Subarea 48.1, respectively (Table A3-3).

This dataset indicates an absence of catches in Subarea 48.1 during summer (Fig. A3-4). During the winter period, most catches were obtained outside VRZs (Table A3-3). However, 166.66 tonnes (0.15%) were caught inside the Hope Bay VRZ on 3 April 2022 by FV *Antarctic Sea* (Fig. A3-5).

CONCLUSIONS

A total of 9 vessels operated during the fishing season 2021/22. None of them operated in Subarea 48.1 during summer. Accordingly, all vessels complied with the seasonal VRZs.

By contrast, one vessel fished inside Hope Bay VRZ on 3 April 2022, catching a total of 166.66 tonnes, in violation of the annual VRZ agreement.

Table A3-1. Synopsis of the krill fishing season 2021/2022 (1 December 2021 to 30 June 2022).

	Subarea 48.1	Subarea 48.2
Max No. fishing vessels	9	9
Subarea closure	27 June	NA
Total Catch (tons)	142,703.73	181,740.81
% Subarea quota	92.1%	65.1%

Table A3-2. List of krill fishing vessels operating in the 2021/22 season and information available to describe their distribution. Haul-by-haul data was provided by some ARK Members (under 'haul-by-haul data'). AIS information was obtained from www.MarineTraffic.com.

COMPANY	VESSEL NAME	Haul-by-Haul data	AIS information
PescaChile	Antarctic Endeavour	YES	YES
JEONG-IL	Sae In Leader	YES	YES
AKER BIOMARINE	Antarctic Sea	YES	YES
	Saga Sea	YES	YES
	Antarctic Endurance	YES	YES
DONGWON	Sejong	YES	YES
CNFC	Long Teng	**NO**	YES
	Long Fa	**NO**	YES
Fujian Zhengguan	Fu Yuan Yu 9818	**NO**	YES

Table A3-3. Distribution of catches inside and outside of the VRZs during Summer (Dec-Feb) and Winter (Mar-June) of 2021/22, as reported to ARK.

	Summer	Winter (ton)
Inside VRZs	0%	19.55%
Inside Hope Bay VRZ	0%	0.15%
Outside VRZs	0%	80.45%
Subtotal for Subarea 48.1 (CCAMLR Secretariat)	0 ton	142,703.73 ton
ARK dataset/total catch	*100%*	*79.91%*

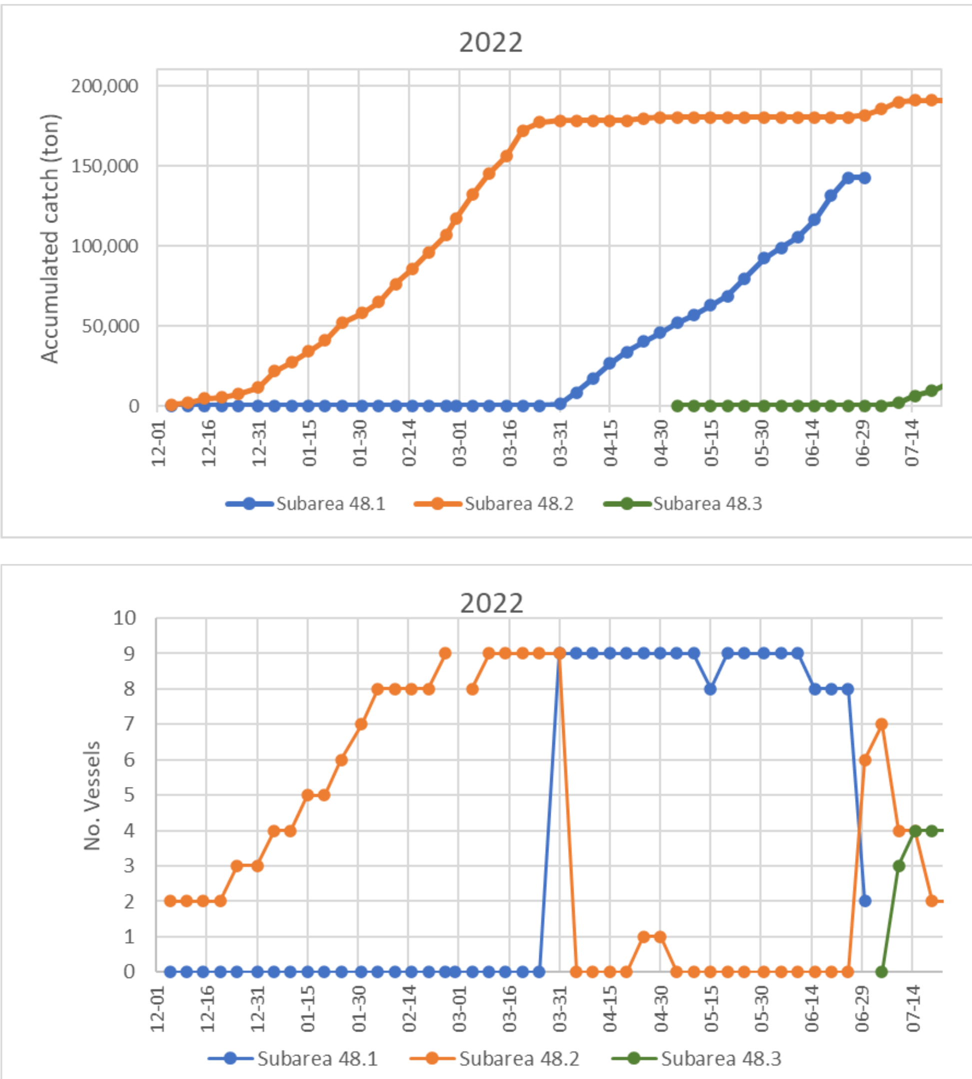


Figure A3-1. Accumulated krill catches (*top*) and the number of fishing vessels operating (*bottom*) as reported by CCAMLR.

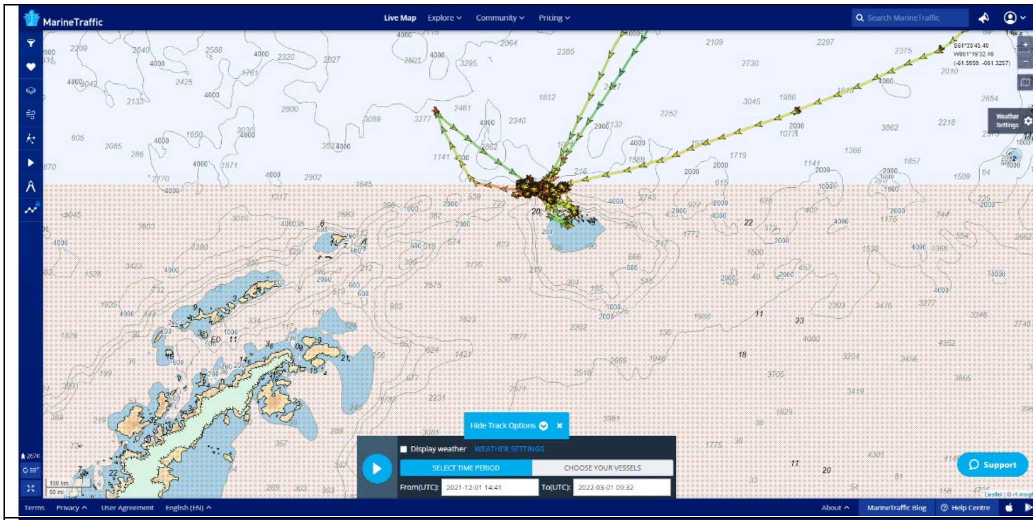
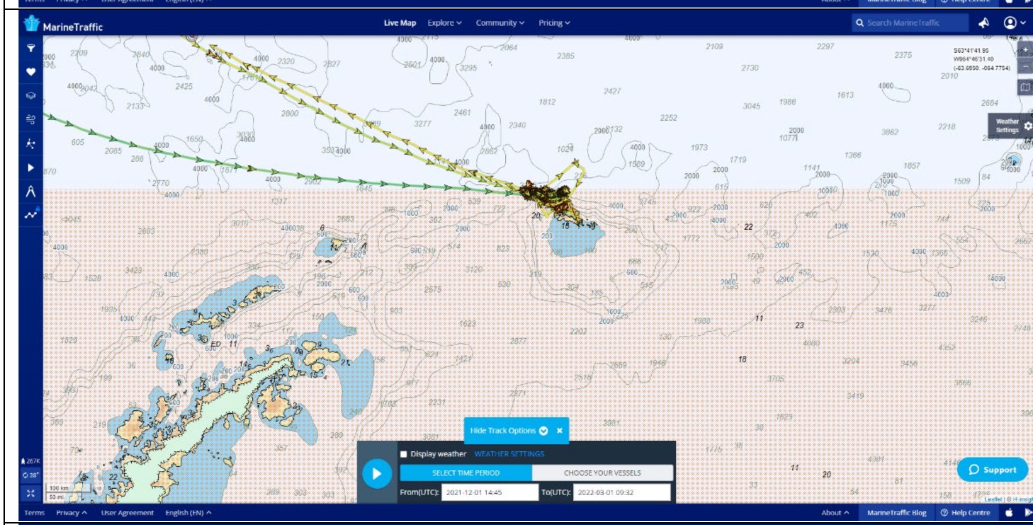
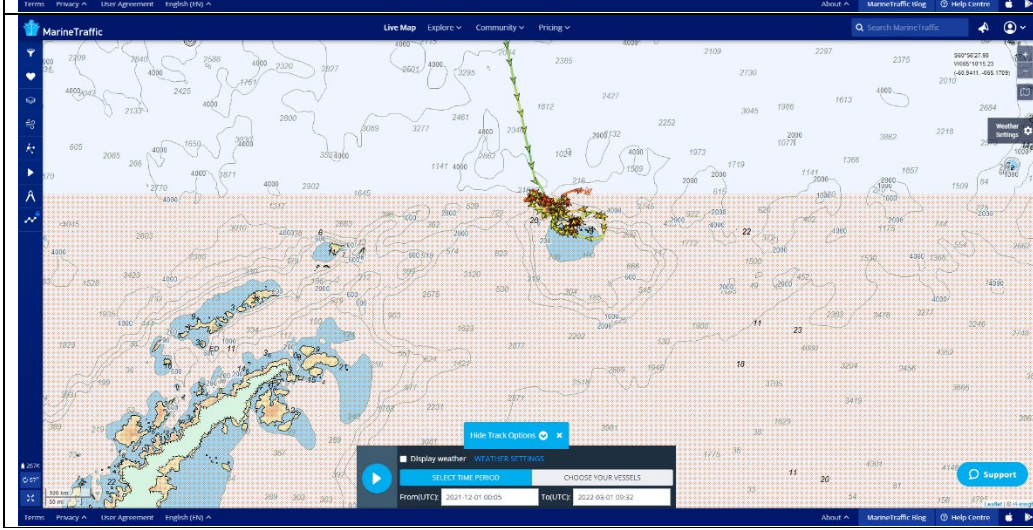
	Chinese fleet
	Korean and Chilean fleet
	Norwegian fleet

Figure A3-2. Distribution of the krill fishing fleet during the summer period (1 December 2021 to 28 February 2022), as obtained from MarineTraffic.com.

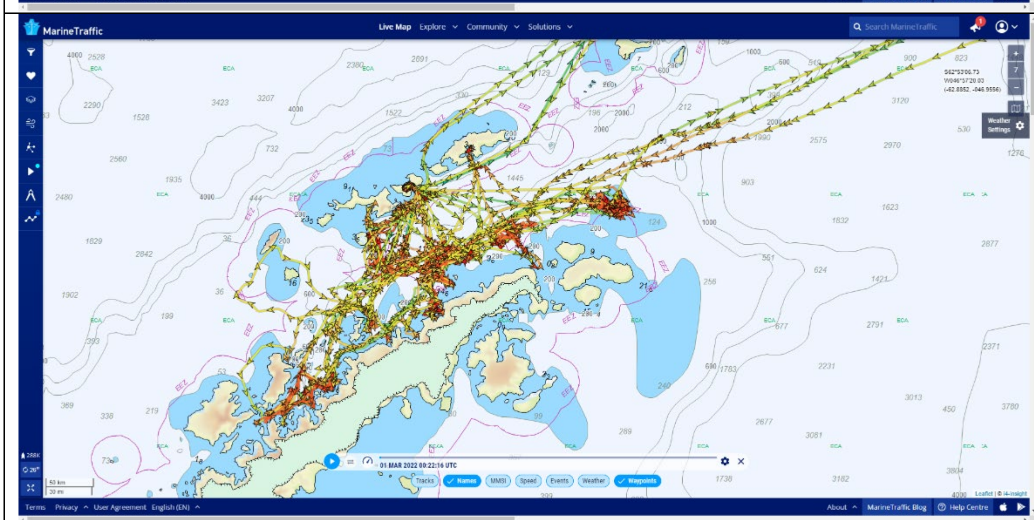
	Chinese fleet
	Korean and Chilean fleet
	Norwegian fleet

Figure A3-3. Distribution of the krill fishing fleet during the winter period (1 March to 30 June 2022), as obtained from MarineTraffic.com.

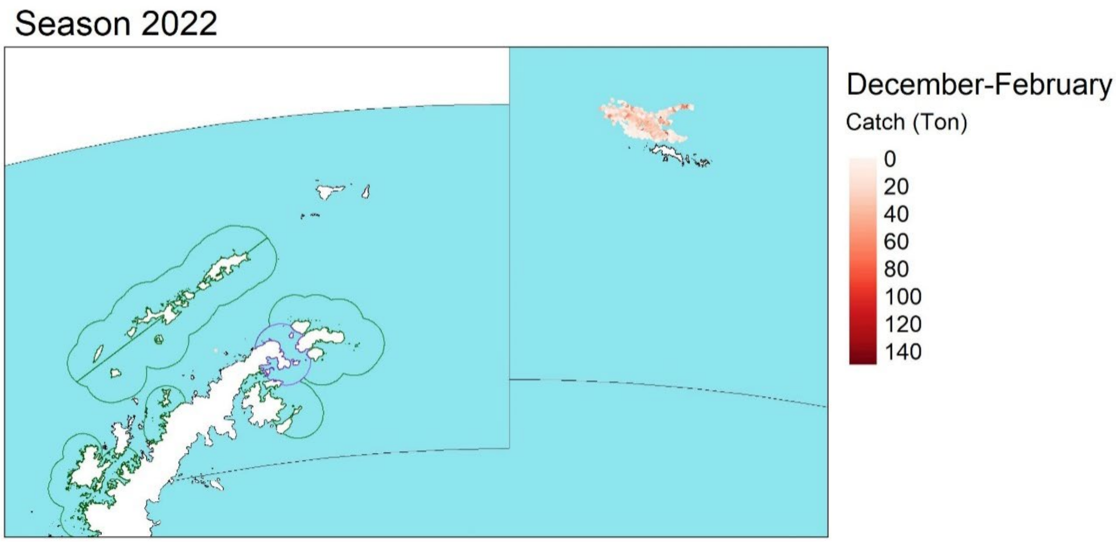


Figure A3-4. Distribution of accumulative krill catches of 6 ARK vessels during the summer of 2021/22 fishing season (see Table 2 for a list of vessels). Source: ARK database.

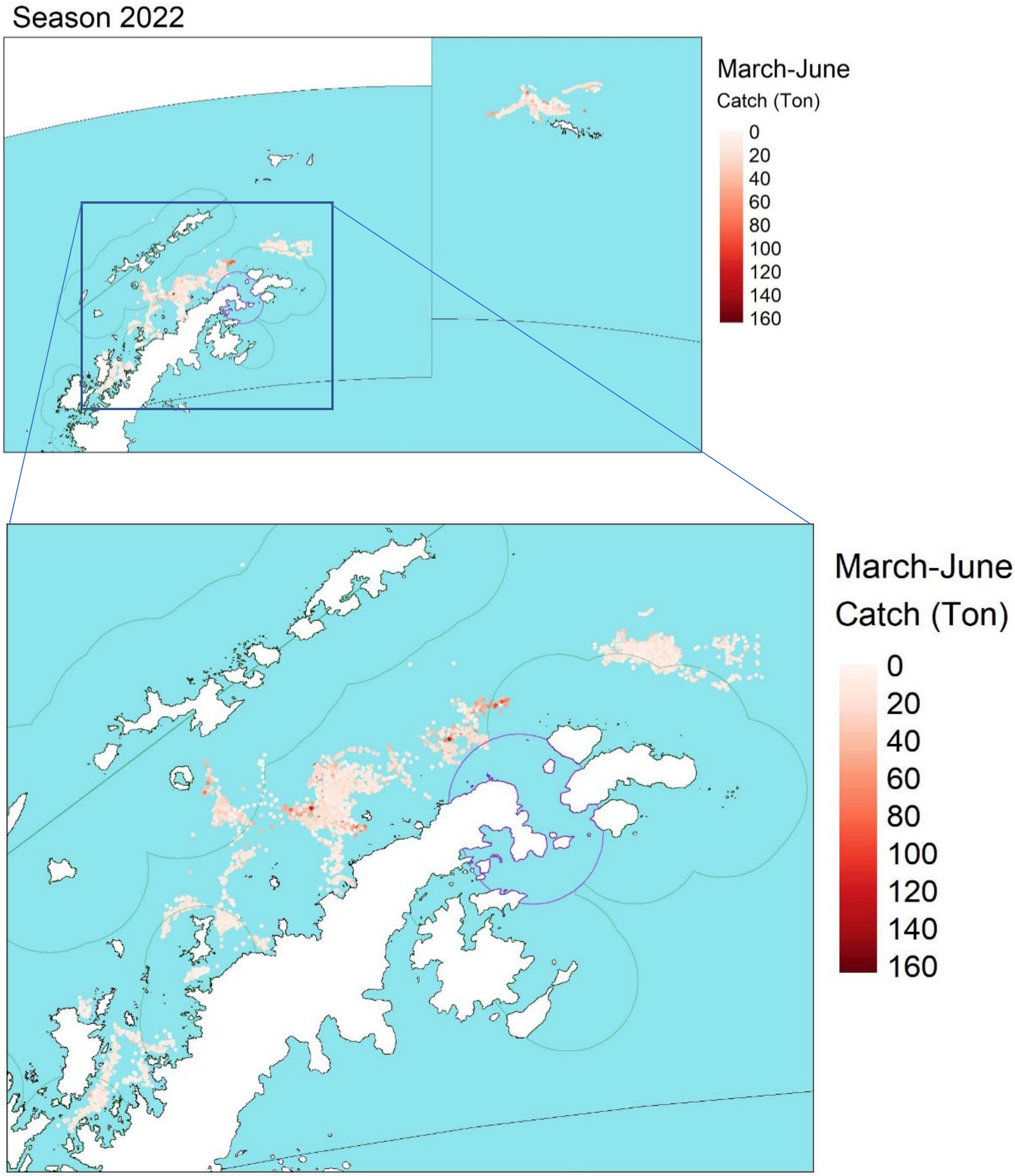


Figure A3-5. Distribution of accumulative krill catches of 6 ARK vessels during winter of 2021/22 fishing season (see Table 2 for a list of vessels). Source: ARK database.

EFFECTS OF THE IMPLEMENTATION OF VRZs IN THE KRILL FISHERY

Dr J.A. Arata (ARK)

INTRODUCTION

The management of the krill fishery is experiencing several changes in the last decade. In 2009 CCAMLR introduced a subdivision of the trigger level among subareas. Later, ARK implemented seasonal Voluntary Restricted Zones (VRZs) on 1 December 2018 to safeguard the main reproductive colonies of penguins in Subarea 48.1. Currently, the Scientific Committee of CAMLR is discussing the implementation of fishing strata for subdividing the fishing quota in Subarea 48.1 (Fig. A3-6).

This report analyzes the impact of these management and operational changes on the temporal and spatial distribution of krill catches.

METHODS

Data Availability

Analyses were conducted for seasons 2012/2013 – 2021/2022 using haul-by-haul data from four ARK members, accounting for seven vessels, provided to the ARK database. Data was imported from Excel sheets, and a preliminary cleaning was performed as follows: data with no catches were removed; hauls positions were filtered and corrected when obvious (i.e., -420.6 instead of -42.06), using positions for preceding/following three hauls; date mistakes were corrected when obvious. Clean data was processed as follows: haul distribution was estimated as the middle point between the start and end of each tow; distance between hauls was estimated, and then data was filtered for speed estimates above 15 knots.

Data from December to February was assigned as "summer" and from March to June as "winter"; data after June was not considered due to data gaps most years. Seasons are referred to by the year they end (i.e., season 2012/13 = 2013).

Data available to ARK was compared with reported catches per season provided by CCAMLR in their annual report.

Data Analysis

All analyses were run in R 4.2.0 (R Core Team 2022) under RStudio 2022.02.3 GNU. Packages used for analyses included the following: data manipulation: 'readr', 'openxlsx', 'dplyr', tidyverse', 'lubridate', 'reshape'; spatial analysis: 'sf', 'raster', 'units'; visualization: 'ggplot2', 'ggformula', 'gghalves', 'tmap'.

Spatial analyses were conducted using the South Pole Lambert Azimuthal Equal Area Projection, centred at longitude 50°W.

Catch distribution

Haul-by-haul catches were assigned to a specific Subarea, VRZ, and Strata (Fig. A3-6) and further subdivided into “summer” and “winter” periods. Yearly data on total catches by period were estimated using ARK’s database.

Changes in catch distribution since the introduction of VRZ, including changes in strata used before and after, were assessed through an ANOVA with Tukey’s Honest Significant Differences post-doc analysis. Seasons/strata/VRZ/periods with no catches were added with ‘0’ values before running the ANOVA.

Footprint analysis

Summary catches by small spatial units (SU) were used to measure changes in the spatial and temporal footprint of the fishery. A hexagonal grid with a radius of 15km (height = 30km, area = 779.43 km2) was used as a proxy of the daily operational impact of the fleet after Watters and Hinke (2022). Catches were summarised by summer and winter periods, fishing strata, and seasons.

The footprint of the fishery was measured by two indices, catch density (tonnes/km2) and fishing effort (no. fishing days). Catch density was estimated by dividing total catches within a SU or hexagon for a specific season/period combination by the actual area of the SU. Fishing effort was estimated by adding all days with a haul (all vessels combined) recorded within a SU for a specific season/period combination. SU smaller than 1/3 of a whole SU were joined with a neighbouring SU; this was particularly important for the GS stratum (Fig. S3).

Trend analyses were conducted using *lm* function applied to SUs, which contained 90% of total catches.

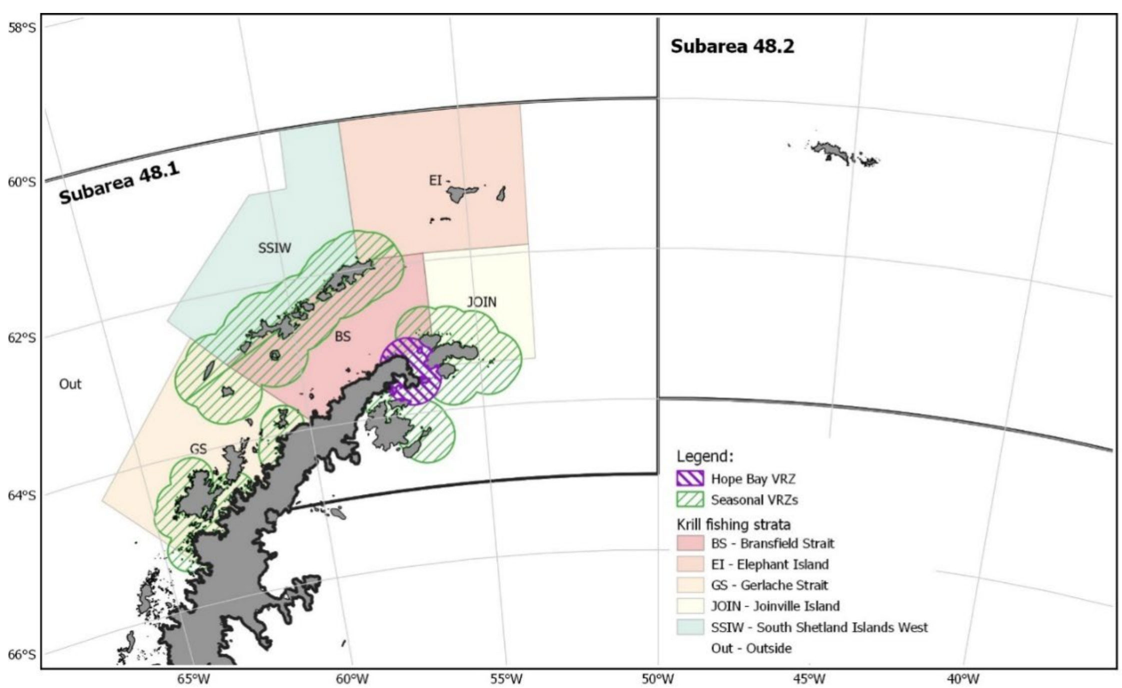


Figure A3-6. Map depicting the main area of interest, including the VRZs and fishing strata units.

RESULTS

Available Data

Catches in subarea 48.1 had remained stable at around 155,000 tonnes for the years analyzed. By contrast, catches in Subarea 48.2 have increased threefold since 2018 (Fig. A3-7, *left*).

Data submitted to ARK, and used in this report, represent on average 61% (30%-80%) and 75% (41%-96%) of total catches reported by CCAMLR for Subareas 48.1 and 48.2, respectively (Fig. A3-7, *right*).

Catch distribution during summer and winter

The temporal and spatial distribution of catches in Subarea 48.1 has changed since the implementation of VRZs in the 2019 fishing season.

The fleet used to fish mainly in VRZ Shetlands and VRZ Gerlache North during summer, but they have ceased since the implementation of VRZs in 2019 (Fig. A3-8). These two VRZs are also important fishing grounds during winter, although their importance has decreased since 2019 (Fig. A3-8).

Overall, catches during summer (December-February) had decreased significantly (one-way ANOVA, $p = 0.0327$), from a pre-VRZ average of 13,869 tonnes per season (Q1-Q3 = 6,638-18,887 ton/season), to a post-VRZ average of 5,753 tonnes per season (Q1-Q3 = 3,739-7,768 ton/season), all caught outside the VRZs (Table 1, Fig. A3-9). This difference is driven by a cessation of catches inside VRZs (Tukey's HSD, $p = 0.0848$), while catches outside remained similar (Tukey's HSD, $p = 0.9002$).

Conversely, catches during winter (March-June) had increased, from a pre-VRZ average of 73,646 tonnes per season (max = Q1-Q3 = 60,126-93,315 ton/season) to a post-VRZ average of 104,879 tonnes per season (Q1-Q3 = 100,654-107,468 ton/season), although differences are not significant (one-way ANOVA, $p = 0.275$) (Table A3-4). Catches outside VRZs had increased significantly (Tukey's HSD, $p = 0.0191$), while catches inside VRZs have remained similar (Tukey's HSD, $p = 0.9101$) (Fig. A3-9).

In Subarea 48.2 there has been a significant increase in catches after the introduction of VRZ in subarea 48.1, both during summer (one-way ANOVA, $p = 0.0031$) and winter (one-way ANOVA, $p = 0.0664$) (Table A3-4, Fig. A3-10). During summer catches had been increasing during the whole study period (lm: slope = 11,642, $p = 0.0001$).

Allocating catches to the proposed fishing strata provides a similar picture. Catches were obtained mainly from Bransfield (BS) and Gerlache Strait (GS) strata, with sporadic high catches in South Shetland Island West (SSIW) and Joinville Island (JOIN) strata (Fig. A3-11). Overall, there had been a significant reduction of catches during summer since VRZ were implemented (ANOVA, $p = 0.0578$), driven by changes in GS, where catches inside VRZs had reduced significantly since 2019 (Tukey's HSD, $p = 0.0565$; Table A3-5). Similarly, winter catches have also changed significantly since the implementation of VRZs (ANOVA, $p = 0.0000$), driven by a significant increase in the use of BS outside VRZs (Tukey's HSD, $p = 0.0024$; Table A3-5).

Table A3-4. Effect of introduction of VRZ in catch distribution. Test conducted using ANOVA, with Tukey's HSD post-hoc analysis. Era = before and after implementation of VRZs. VRZ = inside (s48.1 VRZ) or outside VRZs.

Subarea 48.1

Period	Variables	Pr(>F)
Summer	Before VRZ – after VRZ	0.0327 *
	before:outside - after:outside	0.9002
	before:s48.1 VRZ - after:s48.1 VRZ	0.0848 .
Winter	Before VRZ – after VRZ	0.2750
	before:outside - after:outside	0.0191 *
	before:s48.1 VRZ - after:s48.1 VRZ	0.9101

Subarea 48.2

Period	Variables	Pr(>F)
Summer	Before VRZ – after VRZ	0.0031 *
Winter	Before VRZ – after VRZ	0.0664 .

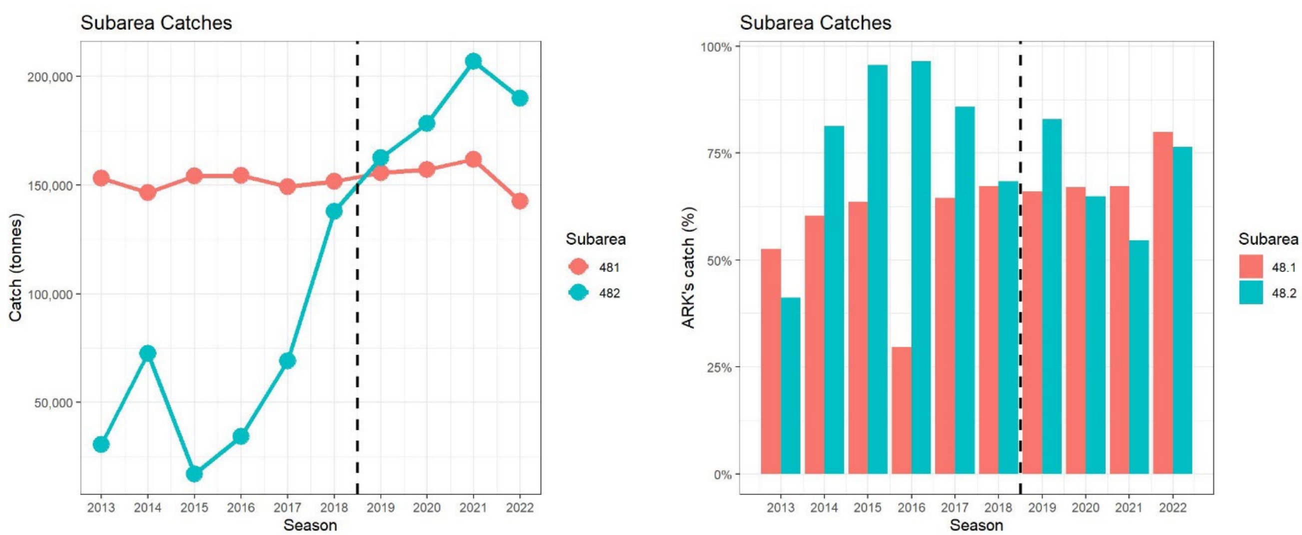


Figure A3-7. (*left*) Total catches reported by CCAMLR in Subareas 48.1 and 48.2; (*right*) fraction of catches represented in ARK's database. Vertical dashed line: implementation of VRZs.

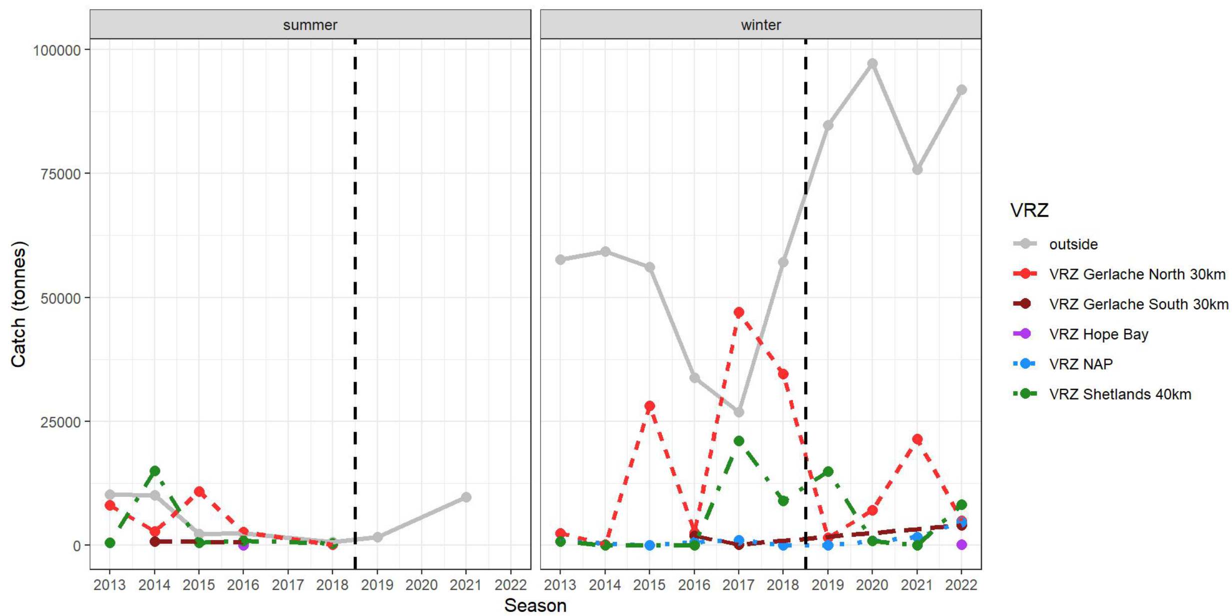


Figure A3-8. Distribution of catches within individual VRZs (Subarea 48.1), during summer and winter periods. Vertical dashed line: implementation of VRZs.

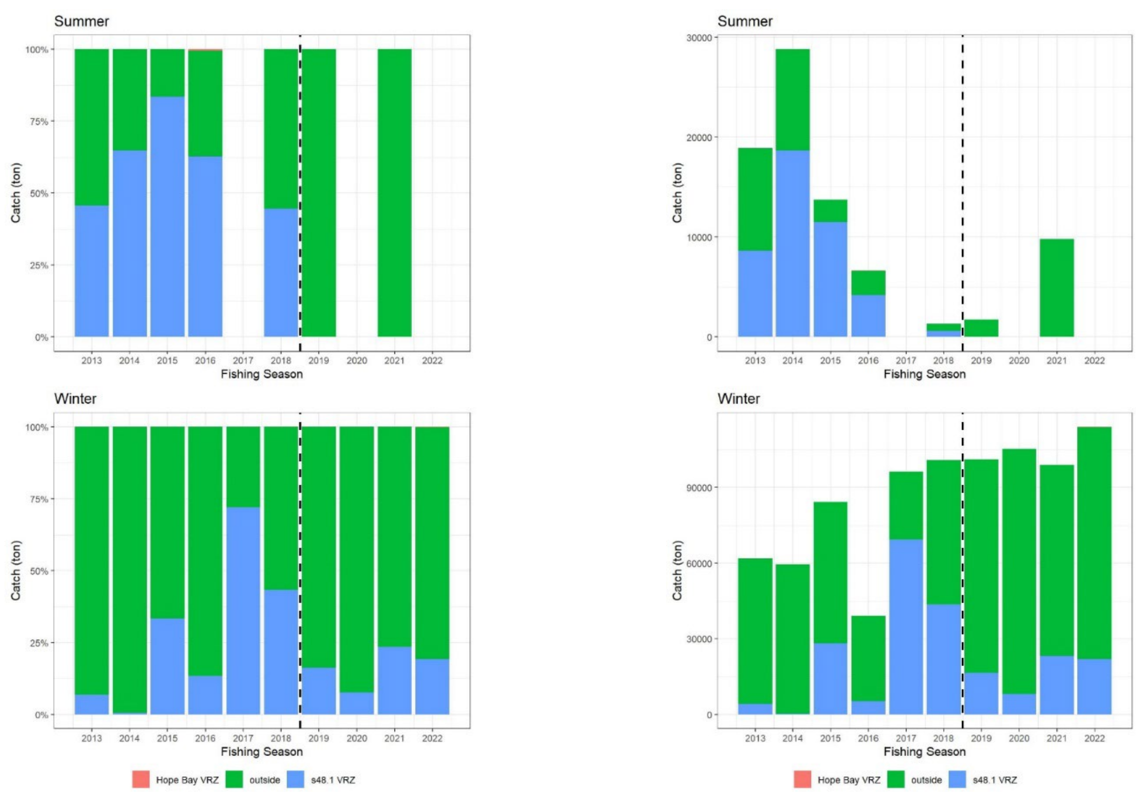


Figure A3-9. Distribution of catches inside and out of VRZs (Subarea 48.1), during summer and winter periods. *Left*: percentage; *Right*: actual catches. Vertical dashed line: implementation of VRZs.

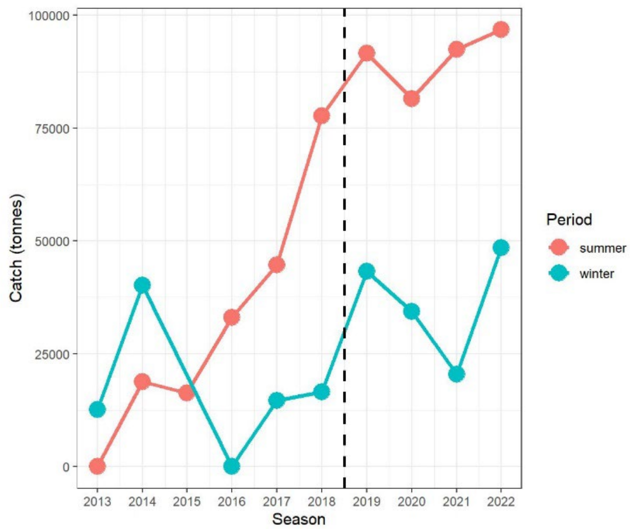


Figure A3-10. Seasonal distribution of catches in Subarea 48.2 for summer and winter (source: ARK database).

Table A3-5. Effect of introduction of fishing strata and VRZ in catch distribution at Subarea 48.1. Test conducted using ANOVA, with Tukey's HSD post-hoc analysis. Era = before and after implementation of VRZs; Strata = fishing strata shown in Figure A3-6; VRZ = inside or outside VRZs.

Period	Variables	Pr(>F)
Summer	ALL: era:Strata	0.0824 .
	before:BS-after:BS	0.9999
	before:EI-after:EI	1.0000
	before:GS-after:GS	0.2230
	before:JOIN-after:JOIN	1.0000
	before:SSIW-after:SSIW	0.9367
	before:BS:outside - after:BS:outside	0.9999
	before:BS:VRZ - after:BS:VRZ	1.0000
	before:GS:outside - after:GS:outside	1.0000
	before:GS:VRZ - after:GS:VRZ	0.0565
Winter	era:Strata	0.0000 *
	before:BS-after:BS	0.7407
	before:EI-after:EI	1.0000
	before:GS-after:GS	1.0000
	before:JOIN-after:JOIN	0.9999
	before:SSIW-after:SSIW	1.0000
	before:BS:outside - after:BS:outside	0.0024
	before:BS:VRZ - after:BS:VRZ	1.0000
	before:GS:outside - after:GS:outside	0.7213
	before:GS:VRZ - after:GS:VRZ	0.9576

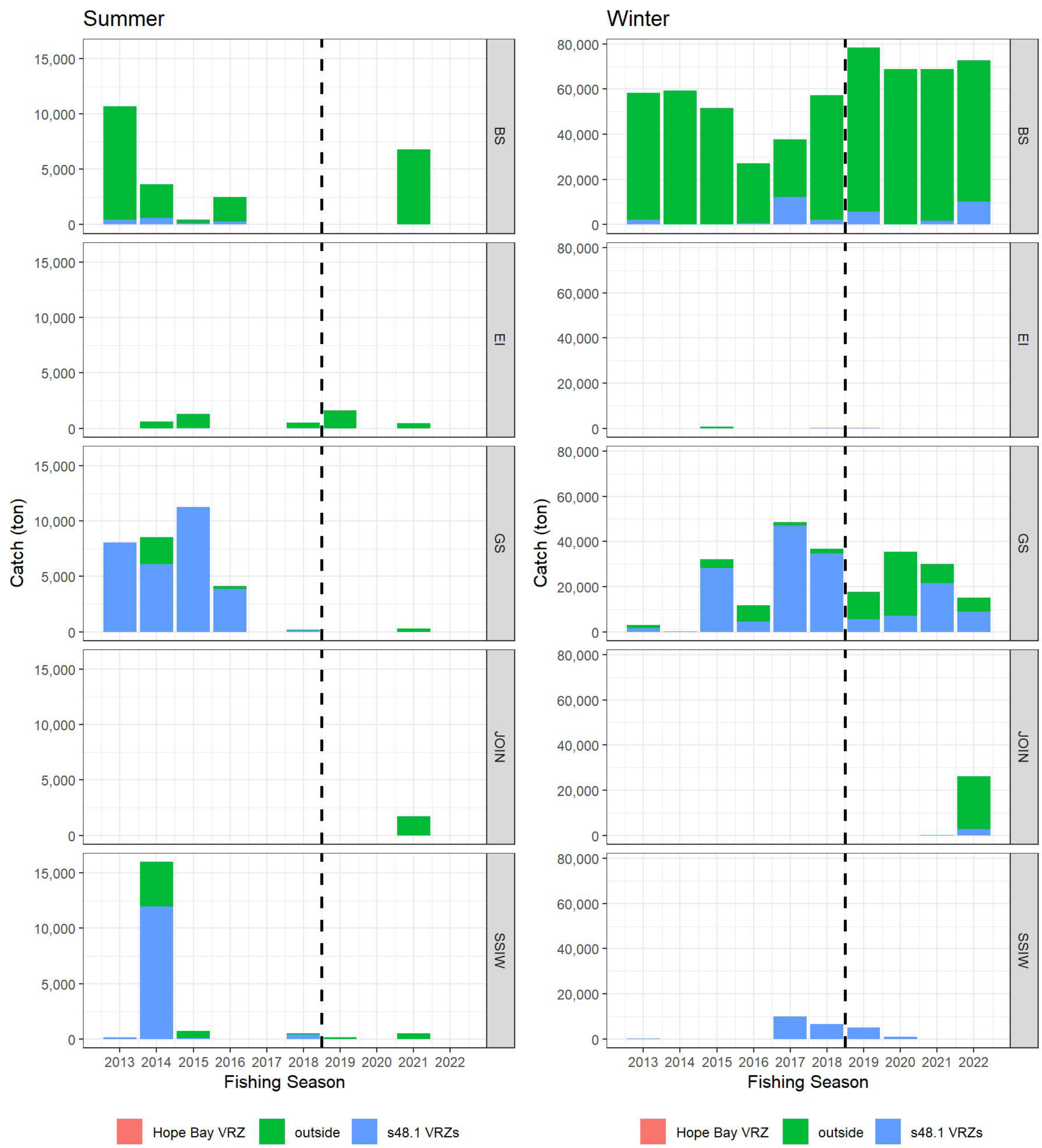


Figure A3-11. Distribution of catches inside and out of VRZs (Subarea 48.1), subdivided by summer/ winter periods and fishing strata (BS = Bransfield Strait, EI = Elephant Island, GS = Gerlache Strait, JOIN = Joinville Island, SSIW = South Shetland Islands West). Vertical dashed line: implementation of VRZs.

Fishery footprint

The fleet presents marked preferences for some spatial units (hexagons) within each subarea. In Subarea 48.1, an average of 5 SUs (catch density, mean = 16.35 ton/km2) contained >50% of all catches each season (range: 3-7 SUs), with main concentrations observed during winter. Likewise, an average of 2 SUs (catch density, mean = 34.87 ton/km2) contained >50% of krill catches each season in Subarea 48.2 (range: 1-5 SUs), with concentration occurring mainly during summer (Fig. A3-12).

However, there is considerable inter-annual variability in catch density and fishing effort, with most catch and effort being concentrated in strata BS and GS in Subarea 48.1 (Fig. A3-13). Catch density and fishing effort across all SU (Spatial Units or hexagons) in BS averaged 2.55 ton/km2 (= g/m2) and 9.3 days/SU, respectively, although considerable interannual variability is observed. Four SUs (out of 27) consistently had higher catch densities (range: 20.9 - 36.3 ton/km2) and fishing effort (range: 41 – 63 days/SU) during 5 out of 10 winters (Table A3-6, Fig. A3-13).

In the GS stratum, the mean catch density and fishing effort for the study period is 2.37 ton/km2 and 8.3 days/SU, respectively. Two SUs (out of 12) had high catch densities (range: 23.3 – 50.3 ton/km2) and fishing effort (range: 31 – 66 days/SU) during 4 out of 10 winters (Table A3-7, Fig. A3-13).

Strata EI and JOIN had low catch density and fishing effort throughout the study period; SSWI strata had low catch density, despite the fishing effort being >20 days in some seasons (Fig. A3-13).

Average catch density in BS increased significantly (one-way ANOVA, $p = 0.0556$) since the implementation of VRZs; however, no differences in catch density, nor a significant trend, within summer or winter were observed (Table A3-10, Fig. A3-14). By contrast, no changes in the overall catch density were observed in GS (two-way ANOVA, $p = 0.8110$), or within summer or winter since the implantation of VRZs. However, catch density and fishing effort showed a significant, positive trend GS during winter (Table A3-11, Fig. A3-14).

The average catch density and fishing effort in Subarea 48.2 was 4.8 ton/km2 and 10.8 days/SU, respectively. However, considerable variability in catch and effort between seasons and SUs was observed (Fig. A3-15). Three SUs (out of 20) consistently had higher catch densities (range: 20.5 - 88.3 ton/km2) and fishing effort (range: 35 – 77 days/SU) during every season from 2017 onwards (Table A3-8, Fig. A3-15). Average catch density increased significantly after the implementation of VRZs (one-way ANOVA, $p = 0.0523$), although no differences were detected within summer or winter. Likewise, no significant trend in footprint within summer or winter was observed (Fig. A3-16).

DISCUSSION

We described changes in catch distribution for 7 vessels affiliated to ARK, from fishing seasons 2013 to 2022, inclusive, representing 61% and 75% of catches reported for Subarea 48.1 and 48.2, respectively.

Catches in Subarea 48.1 had remained stable at ~155,000 tonnes between 2013 and 2022, due to the implementation of the Subarea catch limit in 2009. By contrast, catches in Subarea 48.2 had almost tripled between 2018-2022, compared to 2013-2017 (Fig. A3-7).

The implementation of the seasonal VRZs had produced a change in the fleet behaviour, which used to fish in the Gerlache Strait and north of South Shetland Islands in summer. Nowadays, the whole fleet starts fishing in Subarea 48.2, moving to Subarea 48.1 during mid-to-late March. The former resulted in a significant reduction in summer catches in Subarea 481, driven by a reduction of catches inside VRZs, particularly in the Gerlache Stratum (Table A3-5), and a significant increase in summer catches in Subarea 48.2. Conversely, winter catches in Subarea 48.1 have increased, driven by catches outside VRZs, particularly in the BS stratum (Table A3-5), even after the lift of seasonal closures (Fig. A3-8).

The fleet presents marked preferences for some spatial units (SU) in both Subareas (Fig. A3-12), where ≥50% of the catch is caught. However, catch densities in these SU were still well below the average krill density for each region.

Overall, mean catch density and fishing effort were low at BS (2.55 ton/km2 and 9.3 days/SU), with no observed trend for the study period either in summer or winter. However, catch density has increased since the implementation of VRZs. Similarly, mean catch density and fishing effort in GS were low (2.37 ton/km2 and 8.3 days/SU), but no difference from the implementation of VRZ was detected. However, catch density and fishing effort had a significant, positive trend (Table A3-11, Fig. A3-14).

However, a few SUs at each subarea had significantly higher catches than the other SUs. One or two SUs (out of 27) in BS presented higher catch densities (range: 20.9 - 36.3 ton/km2) and fishing effort (range: 41 – 63 days/SU) during 5 out of 10 winters (Table A3-6, Fig. A3-13). Likewise in GS, one SUs (out of 12) had high catch densities (range: 23.3 – 50.3 ton/km2) and fishing effort (range: 31 – 66 days/SU) during 4 out of 10 winters (Table A3-7, Fig. A3-13). The higher catch densities estimated here these SUs in Subarea 48.1 are still within the average krill density estimated for this subarea. The long-term average krill density for Subarea 48.1 is 55.9 and 26.8 g/m2 (or ton/km2) for SSIW and BS during summer, respectively (Reiss et al., 2017); during winter, the BS strata had a very high krill density (~228 g/m2) although the sample size was small. Recent figures from EMM suggest krill density levels of 34.19 g/m2 (n = 30) and 58.53 gm/2 (n = 1) at BS and GS, respectively (EMM-2022 Report).

Fishing footprint in Subarea 48.2 had a similar pattern, with low mean catch density and fishing effort (4.8 ton/km2 and 10.8 days/SU). Here one or two SUs (out of 20) had higher catch densities (range: 20.5 - 88.3 ton/km2) and fishing effort (range: 35 – 77 days/SU) during every season from 2017 onwards (Table A3-8, Fig. A3-15), a pattern that has been accentuated with the implementation of the VRZs, although no trends were observed (Fig. A3-16). Krill density estimates for Subarea 48.2 average 109.3 g/m2 (range: 10.1 – 301.4 g/m2) for the northern area of the islands (Krafft et al., 2018).

The catch level at these three (5.4% of fished SUs) and two (5.7% of fished SUs) SUs in Subarea 48.1 (BS and GS only) and 48.2 remain at or lower than the average krill density for each region. Furthermore, the fleet seeks hotspots with higher than the average krill concentration, thus, it is likely that the catch ratio is even lower. In Subarea 48.1 particularly, surveys are conducted in summer while the fishery operates in winter, when sporadic data suggest krill density at BS is higher. Finally, catches were obtained over 1 to 2 months, allowing some influx of krill on those SUs.

Nonetheless, carrying out krill surveys concurrent with the fishery (particularly at Subarea 48.1) is urgently needed to assess the localized catch rate of the fishery properly.

References

Krafft, B. A., Skaret, G., Krag , L. A., and Pedersen, R. 2018. Antarctic krill and ecosystem monitoring survey off the South Orkney Islands in 2018. Rapport fra Havforskningen 16-2018. ISSN 1893-4536 (online). https://www.hi.no/hi/nettrapporter/rapport-fra-havforskningen/2018/krilltokt_2018_juvel_krafft_fv_3

Reiss, C. S., Cossio, A., Santora, J. A., Dietrich, K.S., Murray, A., Mitchell,B. G., Walsh, J., Weiss, E. L., Gimpel, C., Jones, C.D., and Watters, G. M. 2017. Overwinter habitat selection by Antarctic krill under varying sea-ice conditions: Implications for top predators and fishery management. Marine Ecology - Progress Series, 568:1-16.

WG-EMM-2022. Report of the Working Group on Ecosystem Monitoring and Management, 4 to 11 July 2022.

R packages:

Auguie, B. 2017. _gridExtra: Miscellaneous Functions for "Grid" Graphics_. R package version 2.3, https://CRAN.R-project.org/package=gridExtra

Bivand, R., and Rundel, C. 2021. _rgeos: Interface to Geometry Engine - Open Source ('GEOS')_. R package version 0.5-9, https://CRAN.R-project.org/package=rgeos

Hijmans, R. 2022. _raster: Geographic Data Analysis and Modeling_. R package version 3.5-15, https://CRAN.R-project.org/package=raster

Kaplan, D., and Pruim, R. 2021. _ggformula: Formula Interface to the Grammar of Graphics_. R package version 0.10.1, https://CRAN.R-project.org/package=ggformula

Pebesma, E. 2018. Simple Features for R: Standardized Support for Spatial Vector Data. The R Journal 10 (1), 439-446, https://doi.org/10.32614/RJ-2018-009

Pebesma, E. J., and Bivand, R. S. 2005. Classes and methods for spatial data in R. R News 5(2), https://cran.r-project.org/doc/Rnews/

R Core Team. 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/

Schauberger, P., and Walker, A. 2021. _openxlsx: Read, Write and Edit xlsx Files_. R package version 4.2.5, https://CRAN.R-project.org/package=openxlsx

Tennekes, M. 2018. _tmap: Thematic Maps in R_. Journal of Statistical Software 84(6), 1-39. https://doi.org/10.18637/jss.v084.i06

Wickham, H. 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York.

Wickham, H., François, R., Henry, L., and Müller, K. 2022. _dplyr: A Grammar of Data Manipulation_. R package version 1.0.8, https://CRAN.R-project.org/package=dplyr

Wickham. H., Hester, J., Bryan, J. 2022. _readr: Read Rectangular Text Data_. R package version 2.1.2, https://CRAN.R-project.org/package=readr

Wickham et al. 2019. Welcome to the tidyverse. Journal of Open Source Software 4(43), 1686, https://doi.org/10.21105/joss.01686

Table A3-6. Statistics of catches per Spatial Unit (SU = 30km-hexagon) for Bransfield Strait stratum, BS (Subarea 48.1).

Season	Period	Strata	No. SU	No. hauls	Catch per SU (tonnes)				Catch density per SU (ton/km2)				Fishing effort (no. days)			
					mean	max	Q 0.1	Q 0.9	mean	max	Q 0.1	Q 0.9	mean	max	Q 0.1	Q 0.9
2013	summer	BS	11	850	972	6408	59	1338	1.26	8.33	0.07	1.72	4.5	15.0	2.0	6.0
2013	winter	BS	18	3789	3242	**18017**	328	9209	4.13	**23.12**	0.42	12.03	18.8	**60.0**	6.0	35.6
2014	summer	BS	13	356	281	1317	19	715	0.36	1.71	0.02	0.92	4.2	13.0	1.0	11.2
2014	winter	BS	17	3670	3492	**25728**	26	8591	4.48	**33.03**	0.03	11.02	15.1	**63.0**	1.0	42.2
2015	summer	BS	6	81	75	181	29	146	0.10	0.23	0.04	0.19	1.8	3.0	1.0	2.5
2015	winter	BS	18	3123	2864	**16263**	34	9069	3.76	**20.88**	0.06	11.66	13.3	**49.0**	1.7	38.2
2016	summer	BS	9	273	279	994	29	706	0.36	1.28	0.04	0.91	2.7	6.0	1.0	5.2
2016	winter	BS	20	2412	1362	5921	10	5189	1.76	7.60	0.01	6.66	12.8	**41.0**	1.0	30.0
2017	winter	BS	27	2292	1397	7940	10	3392	1.83	10.19	0.01	4.59	8.0	39.0	1.0	14.0
2018	summer	BS	1	2	24	24	24	24	0.03	0.03	0.03	0.03	2.0	2.0	2.0	2.0
2018	winter	BS	23	3421	2487	10611	6	6939	3.25	13.62	0.01	9.10	12.3	38.0	1.0	28.8
2019	winter	BS	22	4753	3563	12349	718	7265	4.59	15.85	0.92	9.32	16.3	31.0	6.3	28.9
2020	winter	BS	17	3869	4044	**25543**	15	12579	5.19	**32.78**	0.02	16.14	12.4	**41.0**	1.0	29.2
2021	summer	BS	10	538	681	4292	6	1233	0.88	5.51	0.01	1.58	4.0	11.0	1.0	9.2
2021	winter	BS	18	3949	3823	14855	23	9061	4.88	19.06	0.03	11.77	12.3	**43.0**	1.0	28.5
2022	winter	BS	24	3417	3036	**28098**	30	7246	3.97	**36.25**	0.06	9.30	8.7	**42.0**	1.0	17.5

Table A3-7. Statistics of catches per Spatial Unit (SU = 30km-hexagon) for Gerlache Strait stratum, GS (Subarea 48.1).

Season	Period	Strata	No. SU	No. hauls	Catch per SU (tonnes)				Catch density per SU (ton/km2)				Fishing effort (no. days)			
					mean	max	Q 0.1	Q 0.9	mean	max	Q 0.1	Q 0.9	mean	max	Q 0.1	Q 0.9
2013	summer	GS	6	622	1344	6390	32	3640	1.57	6.76	0.04	4.26	7.3	23.0	1.5	17.5
2013	winter	GS	5	257	619	2207	6	1616	0.66	2.14	0.01	1.67	7.6	26.0	1.0	18.0
2014	summer	GS	8	635	1067	3558	154	2140	1.40	3.77	0.24	2.67	7.0	11.0	3.4	11.0
2014	winter	GS	2	19	107	119	98	117	0.12	0.12	0.12	0.12	2.5	4.0	1.3	3.7
2015	summer	GS	4	877	2817	10073	269	7235	3.12	10.66	0.48	7.70	10.5	30.0	3.0	22.8
2015	winter	GS	10	1958	3199	**18691**	28	12498	4.49	**23.29**	0.04	20.14	10.9	**46.0**	1.0	39.7
2016	summer	GS	10	559	413	2336	27	630	0.53	2.47	0.04	0.84	4.4	15.0	1.0	8.7
2016	winter	GS	7	795	1693	5362	56	4011	2.69	10.58	0.09	6.90	9.3	22.0	3.0	17.8
2017	winter	GS	12	2838	4047	**30334**	45	8621	5.16	**32.11**	0.09	11.42	16.2	**61.0**	1.2	45.8
2018	summer	GS	1	8	214	214	214	214	0.27	0.27	0.27	0.27	3.0	3.0	3.0	3.0
2018	winter	GS	12	1777	3068	**29440**	23	1886	3.54	**31.16**	0.03	3.60	12.1	**66.0**	1.1	18.4
2019	winter	GS	10	967	1763	8044	188	3728	2.25	10.32	0.20	4.83	6.1	14.0	1.9	12.2
2020	winter	GS	11	1596	3231	**25498**	2	7239	5.69	**50.29**	0.00	7.66	8.4	**31.0**	1.0	23.0
2021	summer	GS	1	20	288	288	288	288	0.37	0.37	0.37	0.37	3.0	3.0	3.0	3.0
2021	winter	GS	9	1929	3338	10186	56	7660	4.34	9.89	0.10	9.13	14.1	**39.0**	1.0	31.8
2022	winter	GS	12	1372	1259	3791	513	3053	1.80	5.43	0.85	3.07	10.3	22.0	5.2	16.0

Table A3-8. Statistics of catches per Spatial Unit (SU = 30km-hexagon) for Subarea 48.2.

Season	Period	No. SU	No. hauls	Catch per SU (tonnes)				Catch density per SU (ton/km2)				Fishing effort (no. days)			
				mean	max	Q 0.1	Q 0.9	mean	max	Q 0.1	Q 0.9	mean	max	Q 0.1	Q 0.9
2013	summer	10	15	0	0	0	0	0.0	0.0	0.0	0.0	1.3	2.0	1.0	2.0
2013	winter	5	548	2521	4063	597	3978	3.2	5.2	0.8	5.1	11.0	21.0	4.4	18.2
2014	summer	6	740	3124	7608	760	6917	4.4	10.3	1.0	10.0	8.8	17.0	4.5	16.0
2014	winter	12	2057	3346	**17587**	17	6815	4.4	**22.6**	0.0	8.8	12.4	**41.0**	1.1	28.0
2015	summer	11	1336	1486	5518	28	5432	2.0	7.1	0.0	7.0	8.5	28.0	1.0	26.0
2016	summer	16	1630	2067	13521	8	6792	2.7	17.3	0.0	9.3	7.7	**41.0**	1.0	21.0
2016	winter	3	24	5	8	1	7	0.0	0.0	0.0	0.0	1.3	2.0	1.0	1.8
2017	summer	10	2083	4471	**17966**	85	12293	5.8	**23.1**	0.1	15.8	13.3	**46.0**	2.0	30.7
2017	winter	12	789	1216	4018	21	3967	1.6	5.2	0.0	5.1	4.6	14.0	1.0	11.8
2018	summer	11	3261	7062	**45135**	48	13445	9.4	**57.9**	0.1	17.2	16.4	**73.0**	1.0	30.0
2018	winter	10	1027	1657	10688	2	2418	2.2	13.7	0.0	3.6	10.1	**36.0**	1.0	19.8
2019	summer	10	3984	9157	**68810**	9	16207	12.2	**88.3**	0.0	24.3	19.9	**77.0**	1.9	46.4
2019	winter	7	2379	6186	**26760**	205	16297	8.1	**34.3**	0.3	20.9	17.9	**35.0**	2.8	33.2
2020	summer	11	3827	7412	**58917**	4	8870	9.8	**75.6**	0.0	14.4	20.0	**70.0**	1.0	46.0
2020	winter	10	2428	3431	**18378**	6	11686	4.9	**23.6**	0.0	18.7	12.8	**35.0**	1.0	35.0
2021	summer	20	4613	4619	**43034**	90	11338	6.7	**55.2**	0.1	18.8	9.8	**57.0**	2.0	24.1
2021	winter	11	1705	1864	8991	15	5600	2.9	15.0	0.0	9.3	9.7	24.0	1.0	20.0
2022	summer	16	4302	6048	**15946**	63	13566	8.0	**20.5**	0.1	18.7	13.3	**35.0**	1.0	32.0
2022	winter	19	1971	2552	**17016**	13	5466	3.3	**21.8**	0.0	7.0	6.2	25.0	1.0	12.2

Table A3-9. Footprint trend in Subarea 48.1.

Subarea 481, summer

- Catch density - lm(formula = log(Catch_den) ~ Season:Strata, data = sum.fd1.90)

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	115.06438	103.19738	1.115	0.267
Season:StrataBS	-0.05775	0.05120	-1.128	0.261
Season:StrataEI	-0.05841	0.05116	-1.142	0.256
Season:StrataGS	-0.05734	0.05122	-1.120	0.265
Season:StrataJOIN	-0.05776	0.05106	-1.131	0.260
Season:StrataSSIW	-0.05819	0.05119	-1.137	0.258

- Fishing effort - lm(formula = log(No_days) ~ Season:Strata, data = sum.fd1.90)

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	20.244123	60.900637	0.332	0.740
Season:StrataBS	-0.009616	0.030214	-0.318	0.751
Season:StrataEI	-0.009668	0.030190	-0.320	0.749
Season:StrataGS	-0.009335	0.030226	-0.309	0.758
Season:StrataJOIN	-0.009607	0.030135	-0.319	0.750
Season:StrataSSIW	-0.009616	0.030212	-0.318	0.751

Subarea 48.1, winter

- Catch density - lm(formula = log(Catch_den) ~ Season:Strata, data = win.fd1.90)

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-197.81928	79.12070	-2.500	0.0129 *
Season:StrataBS	0.09810	0.03921	2.502	0.0129 *
Season:StrataEI	0.09668	0.03924	2.463	0.0143 *
Season:StrataGS	0.09779	0.03920	2.494	0.0131 *
Season:StrataJOIN	0.09753	0.03916	2.490	0.0133 *
Season:StrataSSIW	0.09731	0.03922	2.481	0.0136 *

- Fishing effort - lm(formula = log(No_days) ~ Season:Strata, data = win.fd1.90)

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-0.2916919	46.7187215	-0.006	0.995
Season:StrataBS	0.0011172	0.0231546	0.048	0.962
Season:StrataEI	0.0003737	0.0231731	0.016	0.987
Season:StrataGS	0.0009596	0.0231487	0.041	0.967
Season:StrataJOIN	0.0007132	0.0231230	0.031	0.975
Season:StrataSSIW	0.0007918	0.0231567	0.034	0.973

Table A3-10. Footprint trend in Bransfield (BS) stratum.

BS stratum, summer

- Catch density - lm(formula = log(Catch_den) ~ Season, data = BS.sum)

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-61.13364	157.63606	-0.388	0.701
Season	0.02966	0.07821	0.379	0.707

- Fishing effort - lm(formula = No_days ~ Season, data = BS.sum)

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-34.86421	96.34105	-0.362	0.720
Season	0.01773	0.04780	0.371	0.713

BS stratum, winter

- Catch density - lm(formula = log(Catch_den) ~ Season, data = BS.win)

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-68.73396	96.32567	-0.714	0.476
Season	0.03412	0.04774	0.715	0.476

- Fishing effort - lm(formula = No_days ~ Season, data = BS.win)

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	94.54918	56.69657	1.668	0.0971 .
Season	-0.04589	0.0281	-1.633	0.1042

Table A3-11. Footprint trend in Gerlache (GS) stratum.

GS stratum, summer

- Catch density - lm(formula = log(Catch_den) ~ Season, data = GS.sum)

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	235.1033	276.2464	0.851	0.404
Season	-0.1169	0.1371	-0.853	0.403

- Fishing effort - lm(formula = No_days ~ Season, data = GS.sum)

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	211.70673	187.89135	1.127	0.271
Season	-0.1044	0.09325	-1.119	0.275

GS stratum, winter

- Catch density - lm(formula = log(Catch_den) ~ Season, data = GS.win)

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-390.82607	168.83020	-2.315	0.0231 *
Season	0.1934	0.08365	2.312	0.0233 *

- Fishing effort - lm(formula = log(No_days) ~ Season, data = GS.win)

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-158.18891	95.39812	-1.658	0.1011
Season	0.0792	0.0473	1.675	0.0977 .

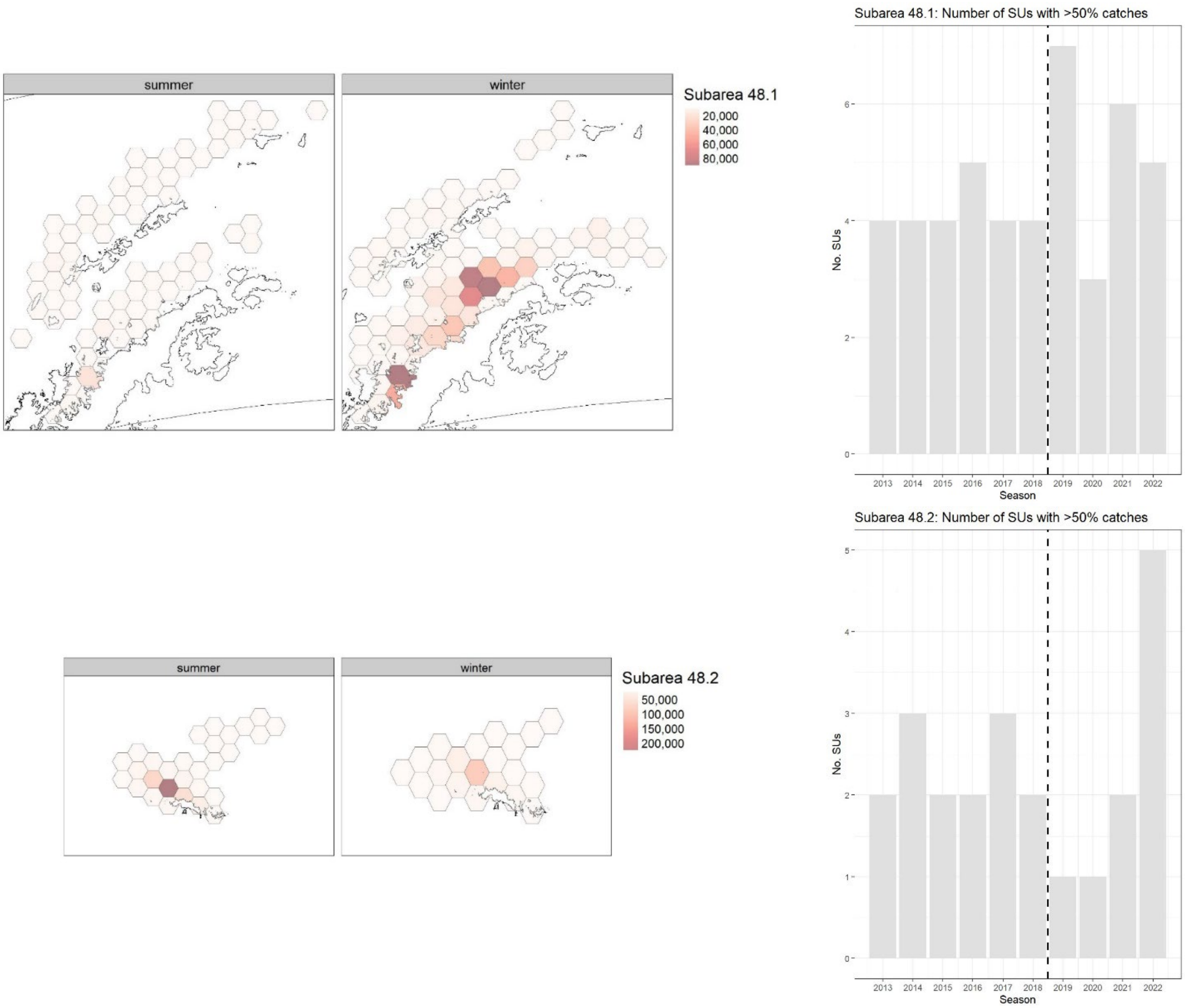


Figure A3-12. Distribution (left) of SUs containing 90% of krill catches, and number of SUs (right) containing >50% of krill catches during seasons 2012/13 to 2021/22. Source: ARK database.

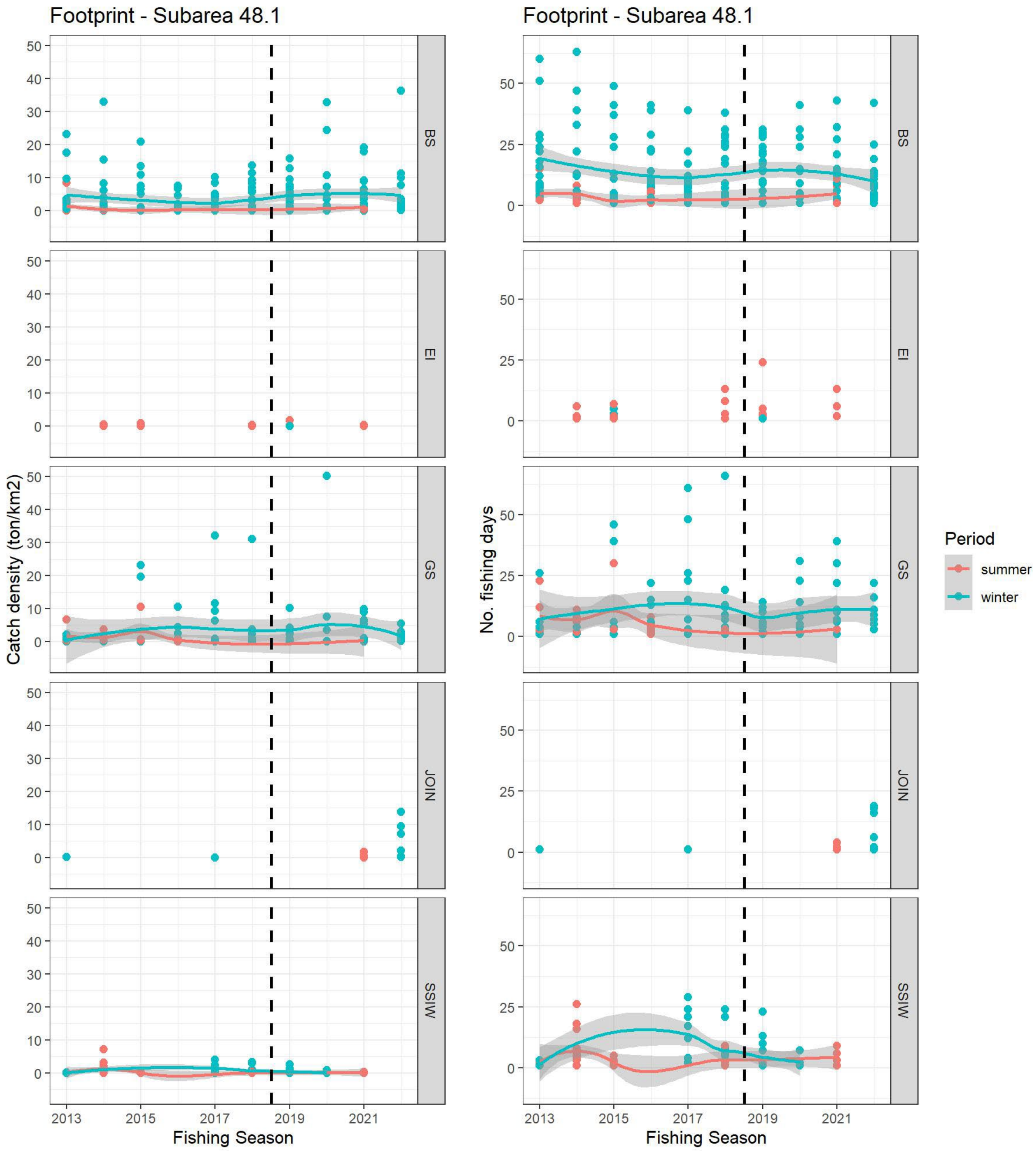


Figure A3-13. Footprint by strata in Subarea 48.1 for SUs from which 90% of the annual catch is taken. Vertical dashed line: implementation of VRZs. Source: ARK database.

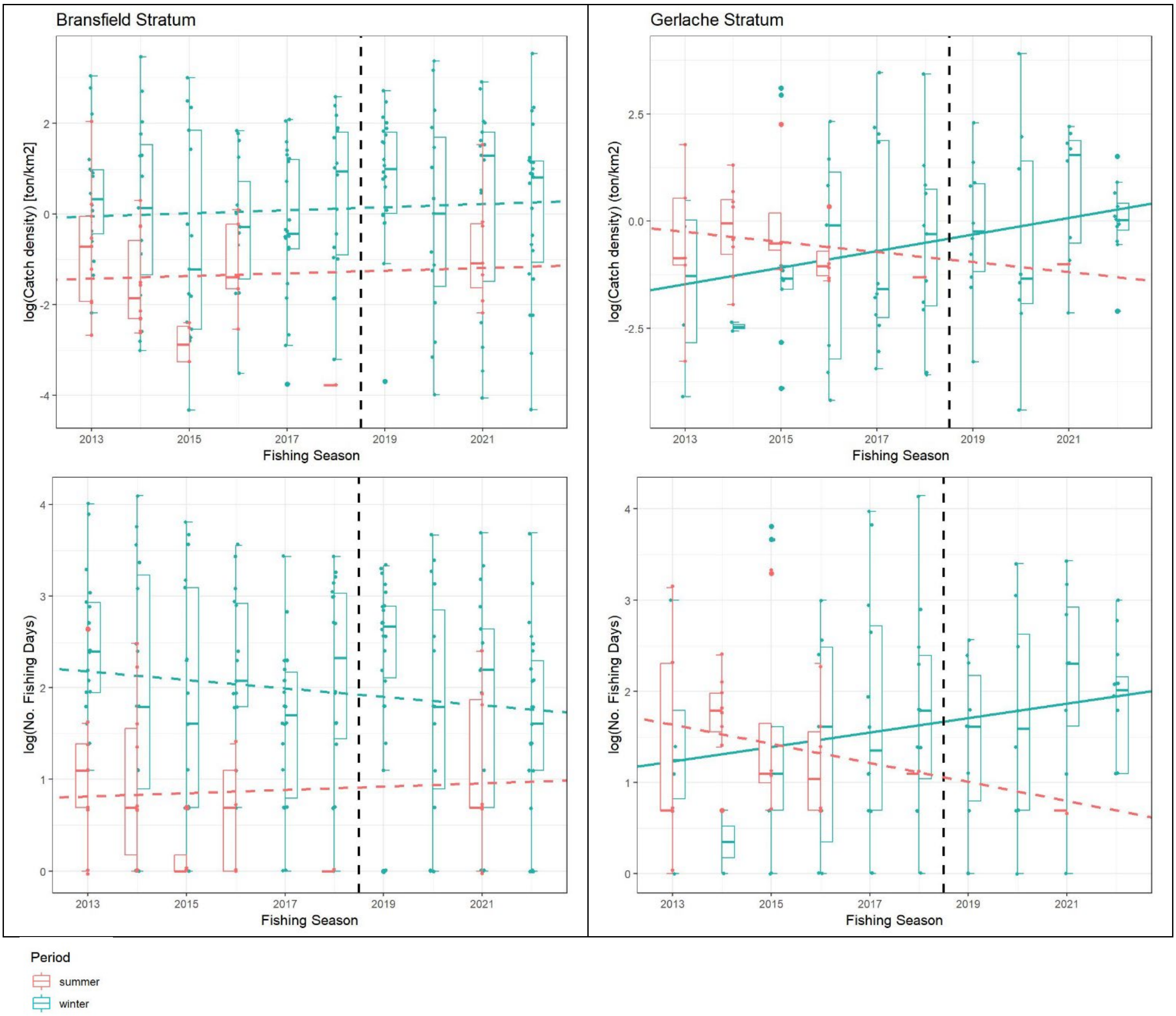


Figure A3-14. Footprint Subarea 48.1 for SUs from which 90% of the annual catch is taken. Dash line: non-significant correlation; Solid line: significant correlation. Vertical dashed line: implementation of VRZs. Source: ARK database.

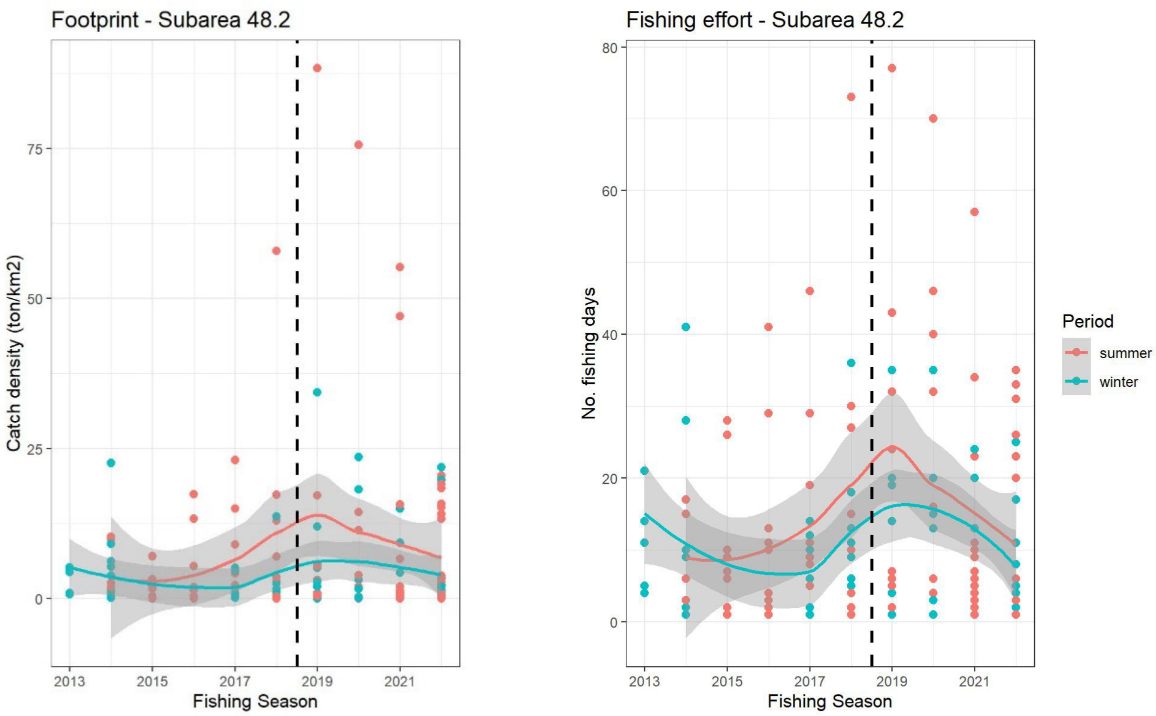


Figure A3-15. Footprint Subarea 48.2 for SUs from which 90% of the annual catch is taken. Vertical dashed line: implementation of VRZs. Source: ARK database.

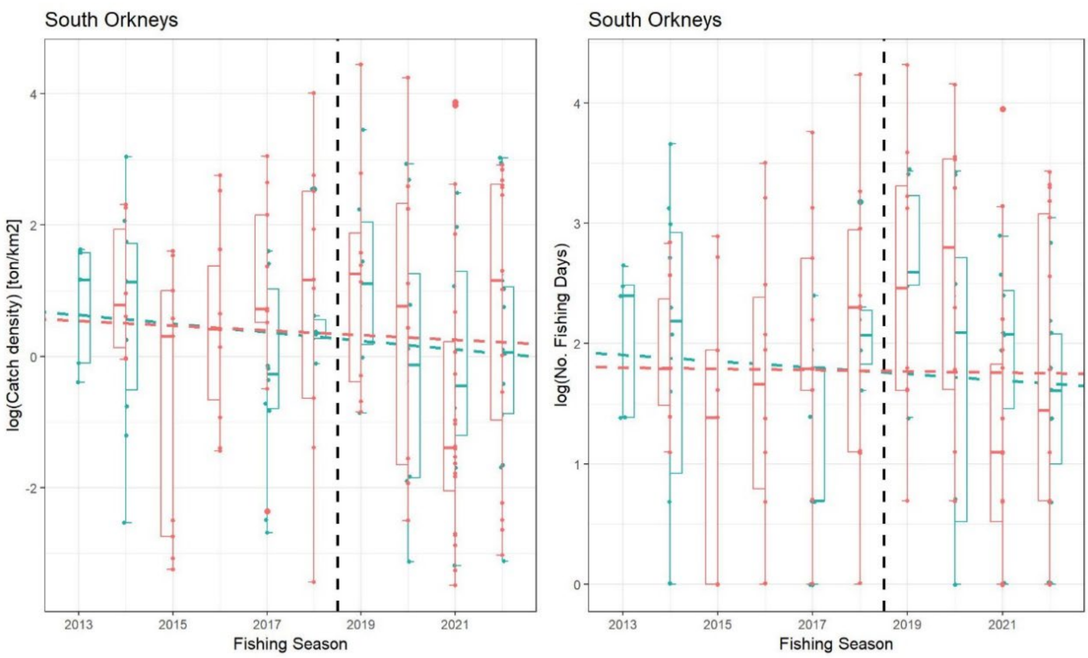


Figure A3-16. Trend in footprint in Subarea 48.2 for SUs from which 90% of the annual catch is taken. Trends: Catch density, summer: log(slope) = -0.0354 ton/km2 per season, *p* = 0.667; Catch density, winter: log(slope) = -0.0653, *p* = 0.313); Fishing effort, summer: log(slope) = -0.0051 days per season, *p* = 0.917; Fishing effort, winter: log(slope) = 0.0265, *p* = 0.524 . Dash line: non-significant correlation; Solid line: significant correlation. Vertical dashed line: implementation of VRZs. Source: ARK database.

Supplement Material

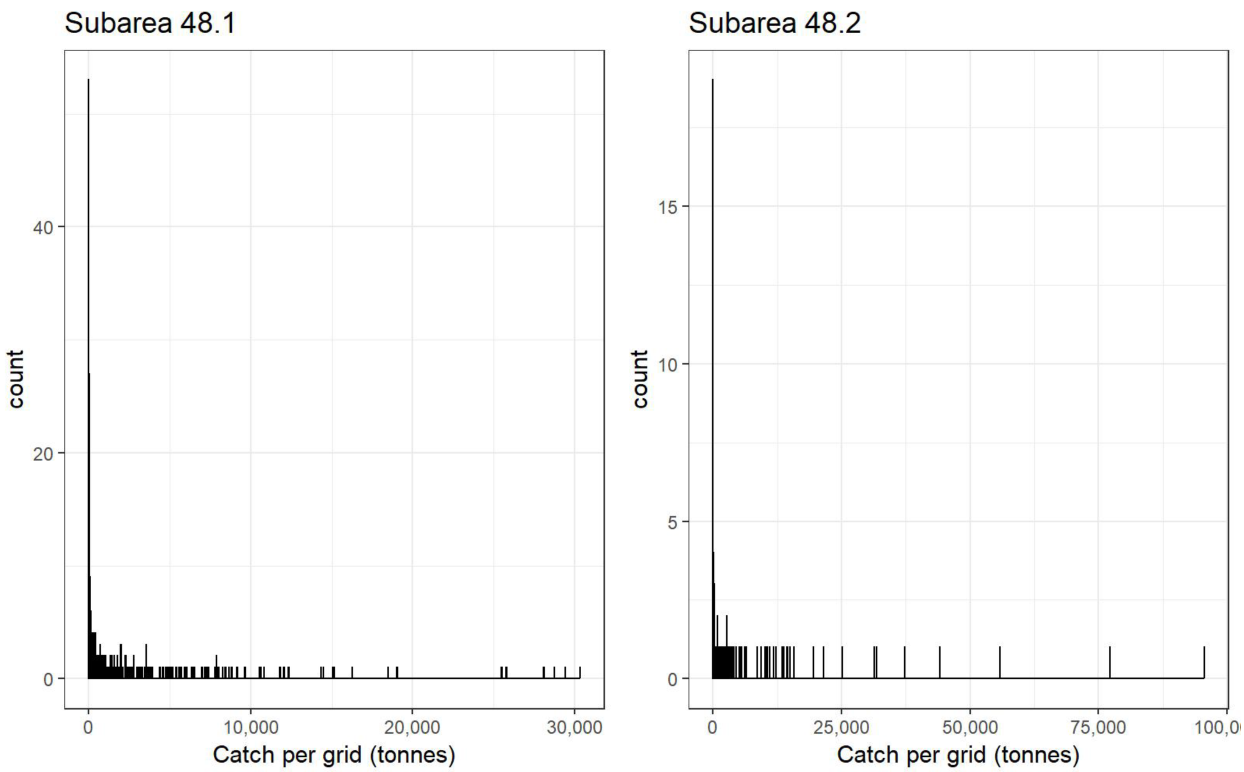


Figure S1. Histogram of catches per hexagon, on 10-ton bins.

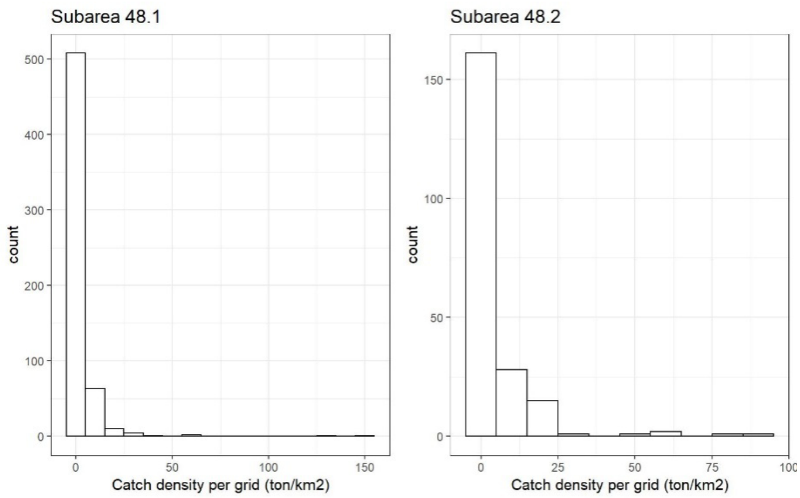


Figure S2. Histogram with catch density per spatial unit (hexagons) for Subrea 48.1 and 48.2.

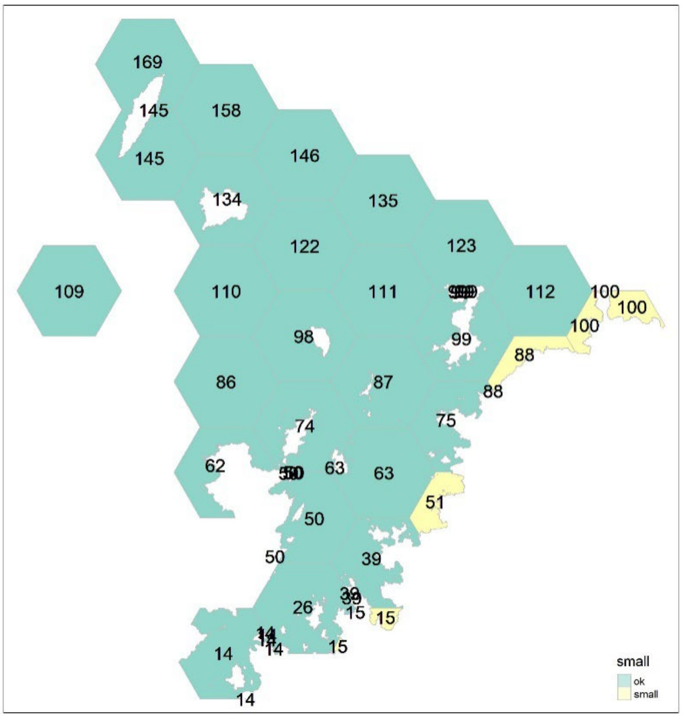


Figure S3. Size of SU I GS strata. Small SUs were joined with adjacent SU.

SU15 -> SU39; SU51 -> SU63; SU88 -> SU99; SU100 -> SU112.

Appendix 4. Detailed report on other predators of krill

Drs H. Herr and R. Reisinger

A study investigating the feeding behavior of 3 penguin, 11 flying bird, 1 pinniped and 2 whale species suggests that the majority of important areas for krill predator foraging are close to penguin breeding colonies in nearshore areas. Attention is drawn to the fact that currently many krill predator species are not considered in krill fishery management. It will be necessary to include abundance and consumption estimates for pack-ice seals, finfish,

squid, and other baleen whale species currently not considered (Warwick-Evans et al., 2022).

Whales

Based on the 2019 synoptic krill survey Baines et al. (2021) estimated a relatively low number of humpback whales (785 individuals, 95% CI = 208−2960) in CCAMLR area 48.2 compared to 48.3 (12,103, 95% CI = 7145−20,499) and 48.4 (11,656, 95% CI = 5865−23,164), which together are thought to form the summer feeding grounds of southwest Atlantic humpback whales (Breeding Stock (BS) A).

Along the western Antarctic Peninsula, corresponding to area 48.1, an abundance of up to 19,107 humpback whales was estimated for the Bransfield and Gerlache Strait, based on data collected from platforms of opportunity in the austral summer of 2019/2020 (Johannessen et al., 2022). This area is traditionally recognized as the feeding grounds of southeast Pacific humpback whales (BS G). However, recently new evidence of summer co-occurrence of BS A and BS G at the western Antarctic Peninsula pointed to a need to revise perceptions of boundaries between stocks and ocean basins (Marcondes et al., 2021). Based on the abundance estimate for the western Antarctic Peninsula, a total krill consumption of between 1.4 and 3.7 million tons krill by humpback whales in the area was projected (Johannessen et al., 2022). However, more recent estimates of prey consumption of baleen whales suggest a threefold higher daily consumption rate of baleen whales than estimates used in this analysis (Savoca et al., 2021).

While low spatio-temporal overlap between humpback and minke whales and krill fishing activity was identified at the western Antarctic Peninsula in November–February, potential for significant interaction later in the feeding season, particularly in April and May, was suggested (Johannessen et al., 2022; Reisinger et al., 2022). A highly localized concentration of krill fishing effort late in the fishing season likely poses a threat by potential for local prey depletion for whales concentrating in the same areas simultaneously (Reisinger et al., 2022). At the same time, results from a tagging study saw a reduction in foraging behavior with the progression of the feeding season (Nichols et al., 2022).

Recent acoustic studies revealed a year-round presence of humpback whales in the Atlantic sector of the Southern Ocean (Schall et al., 2021). A new method for combining regional habitat models allows for range-wide predictions of e.g. humpback whales, including areas for which there are no existing data (Reisinger et al., 2021)

In an area part of 48.1, comprising the waters around Elephant Island and the South Shetland Islands, abundance of fin whales was estimated at 7909 individuals (95% CI 1047–15,743) in summer feeding season, with regular occurrence of large local feeding aggregations of up to 150 animals (Herr et al., 2022). These observations point to a recovery of fin whales and an increase in population numbers, but information on overlap with the krill fishery has not yet been analysed.

Seals

Sexual segregation in feeding distribution was shown in juvenile Antarctic fur seals from South Georgia, with females foraging closer to South Georgia and males foraging further south near the Antarctic Peninsula (Jones et al., 2021). For sub-adult males at the South Shetland Islands predicted foraging habitat overlapped highly with the known distribution of Antarctic krill, and identified the waters off the western Antarctic Peninsula and the Scotia Sea as the core of the distribution area of juvenile and sub-adult male Antarctic fur seals in winter (March et al., 2021). A dramatic decline in population numbers (86% decrease since 2007) in Antarctic fur seals at the South Shetland Islands (SSI) was detected, likely driven by leopard seal predation (increasing since 2001) and worsening summer foraging conditions, i.e., decreasing krill and fish availability. The SSI fur seals represent one of four Antarctic fur seal breeding stocks and their loss would greatly reduce genetic diversity of the species (Krause et al., 2022).

References

Baines, M., Kelly, N., Reichelt, M., Lacey, C., Pinder, S., Fielding, S., Murphy, E., Trathan, P., Biuw, M., Lindstrøm, U., Krafft, B. A., and Jackson, J. A. 2021. Population abundance of recovering humpback whales Megaptera novaeangliae and other baleen whales in the Scotia Arc, South Atlantic. Marine Ecology Progress Series, 676:77-94. https://doi.org/10.3354/meps13849

Herr, H., Viquerat, S., Devas, F., Lees, A., Wells, L., Gregory, B., Giffords, T., Beecham, D., and Meyer, B. 2022. Return of large fin whale feeding aggregations to historical whaling grounds in the Southern Ocean. Sci Rep, 12(1):9458. https://doi.org/10.1038/s41598-022-13798-7

Johannessen, J. E. D., Biuw, M., Lindstrom, U., Ollus, V. M. S., Martin Lopez, L. M., Gkikopoulou, K. C., Oosthuizen, W. C., and Lowther, A. 2022. Intra-season variations in distribution and abundance of humpback whales in the West Antarctic Peninsula using cruise vessels as opportunistic platforms. Ecol Evol, 12(2):e8571. https://doi.org/10.1002/ece3.8571

Jones, K. A., Ratcliffe, N., Votier, S. C., Lisovski, S., Bonnet-Lebrun, A. S., and Staniland, I. J. 2021. Sexual segregation in juvenile Antarctic fur seals. Oecologia, 197(2):339-352. https://doi.org/10.1007/s00442-021-04983-y

Krause, D. J., Bonin, C. A., Goebel, M. E., Reiss, C. S., and Watters, G. M. 2022. The Rapid Population Collapse of a Key Marine Predator in the Northern Antarctic Peninsula Endangers Genetic Diversity and Resilience to Climate Change. Frontiers in Marine Science, 8. https://doi.org/10.3389/fmars.2021.796488

March, D., Drago, M., Gazo, M., Parga, M., Rita, D., and Cardona, L. 2021. Winter distribution of juvenile and sub-adult male Antarctic fur seals (*Arctocephalus gazella*) along the western Antarctic Peninsula. Sci Rep, 11(1):22234. https://doi.org/10.1038/s41598-021-01700-w

Marcondes, M. C. C., Cheeseman, T., Jackson, J. A., Friedlaender, A. S., Pallin, L., Olio, M., Wedekin, L. L., Daura-Jorge, F. G., Cardoso, J., Santos, J. D. F., Fortes, R. C., Araujo, M. F., Bassoi, M., Beaver, V., Bombosch, A., Clark, C. W., Denkinger, J., Boyle, A., Rasmussen, K., Savenko, O., Avila, I. C., Palacios, D. M., Kennedy, A. S., and Sousa-Lima, R. S. 2021. The Southern Ocean Exchange: porous boundaries between humpback whale breeding populations in southern polar waters. Sci Rep, 11(1):23618. https://doi.org/10.1038/s41598-021-02612-5

Nichols, R. C., Cade, D. E., Kahane-Rapport, S., Goldbogen, J., Stimpert, A., Nowacek, D., Read, A. J., Johnston, D. W., and Friedlaender, A. 2022. Intra-seasonal variation in feeding rates and diel foraging behaviour in a seasonally fasting mammal, the humpback whale. R Soc Open Sci, 9(7):211674. https://doi.org/10.1098/rsos.211674

Reisinger, R. R., Friedlaender, A. S., Zerbini, A. N., Palacios, D. M., Andrews-Goff, V., Dalla Rosa, L., Double, M., Findlay, K., Garrigue, C., How, J., Jenner, C., Jenner, M.-N., Mate, B., Rosenbaum, H. C., Seakamela, S. M., and Constantine, R. (2021). Combining Regional Habitat Selection Models for Large-Scale Prediction: Circumpolar Habitat Selection of Southern Ocean Humpback Whales. Remote Sensing, 13(11). https://doi.org/10.3390/rs13112074

Reisinger, R. R., Trathan, P. N., Johnson, C. M., Joyce, T. W., Durban, J. W., Pitman, R. L., and Friedlaender, A. S.2022. Spatiotemporal Overlap of Baleen Whales and Krill Fisheries in the Western Antarctic Peninsula Region. Frontiers in Marine Science, 9. https://doi.org/10.3389/fmars.2022.914726

Savoca, M. S., Czapanskiy, M. F., Kahane-Rapport, S. R., Gough, W. T., Fahlbusch, J. A., Bierlich, K. C., Segre, P. S., Di Clemente, J., Penry, G. S., Wiley, D. N., Calambokidis, J., Nowacek, D. P., Johnston, D. W., Pyenson, N. D., Friedlaender, A. S., Hazen, E. L., and Goldbogen, J. A. 2021. Baleen whale prey consumption based on high-resolution foraging measurements. Nature, 599(7883):85-90. https://doi.org/10.1038/s41586-021-03991-5

Schall, E., Thomisch, K., Boebel, O., Gerlach, G., Mangia Woods, S., El-Gabbas, A., and Van Opzeeland, I. 2021. Multi-year presence of humpback whales in the Atlantic sector of the Southern Ocean but not during El Nino. Commun Biol, 4(1), 790. https://doi.org/10.1038/s42003-021-02332-6

Warwick-Evans, V., Kelly, N., Dalla Rosa, L., Friedlaender, A., Hinke, J. T., Kim, J. H., Kokubun, N., Santora, J. A., Secchi, E. R., Seyboth, E., and Trathan, P. N. 2022. Using seabird and whale distribution models to estimate spatial consumption of krill to inform fishery management. Ecosphere, 13(6). https://doi.org/10.1002/ecs2.4083